Linked Surface Water-Groundwater Model for the Cosumnes River Watershed: Hydrologic Evaluation of Management Options to Restore Fall Flows

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Investigation of Groundwater Surface Water Interactions and their Role in declining Fall River Flows in the Lower Cosumnes Basin

Summary

Chinook salmon fall runs on the Cosumnes River in Sacramento County California have declined as a result of diminishing fall river flows. Investigations of groundwater surface water interactions along the lower Cosumnes River (river-mile 0-36) show that loss of baseflow contributions to the river as a result of groundwater overdraft are at least partly responsible for declining fall flows. Analyses of historical data and results from scenario simulations of regional groundwater flow suggest that the Cosumnes River has received baseflows along its entire lower reaches before the early 1940s. Increasing use of groundwater resources since the 1950s have substantially lowered groundwater levels throughout the county. Major cones of depression in the water-table (upper boundary of the groundwater zone) have formed north and south of the Cosumnes River, with groundwater levels as low as 80 ft below mean sea level at their center. Groundwater levels below the Cosumnes River are currently as low as 55 ft below the river channel, resulting in a hydraulic disconnection between much of the river and the regional aquifer. Most of the lower river does not receive baseflow contributions and the river is in effluent or losing conditions. The hydraulic disconnection is most pronounced in the middle reaches of the lower river between Meiss Road (river-mile 24.8) and Highway 99 (river-mile 11). Around Dillard Road (river-mile 27.3) and Twin Cities Road (river-mile 5) the regional water-table lies closer to the channel elevation and upstream of Dillard Road and downstream of Twin Cities Road groundwater at least seasonally reconnects with the river. River flow in these reaches could be sensitive to further lowering of regional groundwater levels. The lower river is seepage dominated. Seepage rates vary based on river-bed lithology and subsurface stratigraphy. Average flow losses due to seepage losses and losses to riparian evapotranspiration in the summer and early fall are on the order of 1-2 cfs/river-mile.

Regional groundwater simulations suggest that enormous amounts of water per year, 166,000 to 250,000 ac-ft (e.g. as reductions in groundwater pumping or as artificial recharge), would be needed to partly reconnect the river with the regional aquifer, reduce seepage losses and partially reinitiate baseflows. However resulting improvements in fall flows under these measures are comparably small. Flow augmentation with water from Folsom South Canal could provide an alternative. With a 50 cfs flow augmentation from September to December, amounting to approximately 12,000 ac-ft per year, significant flow improvements could be achieved, despite the fact that almost 60% of the augmented flow could be lost to additional seepage.

Surface water simulations were carried out along the reach from Michigan Bar to McConnell in order to quantify the volumes of water needed for surface water flow augmentation. The analysis was conducted with a one-dimensional diffusion wave routing program with an infiltration component. The diffusion wave routing component of the model uses an implicit finite difference scheme with a simple trapezoidal cross section (Anderson, 1993). The infiltration routine is based upon the Green and Ampt method using a Runge Kutta solution technique. Z. Q. Chen supplied the subroutine for the Green and Ampt infiltration. The model was calibrated to a low-flow storm event of December 1999. Using the calibrated model parameters, flow conditions were analyzed for the Michigan Bar to McConnell reach to assess flow requirements at Michigan

Bar to assure a 0.6 feet depth of flow at McConnell. Michigan Bar flows must lie between 60 and 65 cfs in order for the depth at McConnell to be 0.6 feet. With this flow requirement, flow augmentation would be necessary in most years based upon analysis of the last 91 years of flows at Michigan Bar with respect to water year type. For critical water years, a mean value of 3048 acre-feet would have to be supplied for the month of October. For wet years the volume for augmentation of the flow decreases to a mean value of 1124 acre-feet for the month of October. If the channel were to go dry for a given time period, approximately 20 acre-feet of water would be needed to re-establish flow in the channel such that a depth of 0.6 feet exists at McConnell. In addition, approximately 3700 acre-feet per month would be needed to maintain this flow profile. These volumes of water represent a significant portion of the available storage in Sly Park Reservoir (Jenkinson Lake), which is the only reservoir in the watershed. In order to provide the required flow of 60 cfs at Michigan Bar to provide a depth of 0.6 feet at McConnell, approximately 85 cfs would need to be released from Sly Park Reservoir. Over the month of October, this corresponds to a volume of approximately 5225 acre-feet of water.

Long term efforts should address the recovery of regional groundwater levels. Artificial recharge could be a viable means to raise water levels. Efforts to restore a natural flood regime on the lower Cosumnes, where the river can go over-bank during flood flows, could be a significant source of additional recharge as preliminary simulations show. Future work needs to further address the geologic complexity of the local river aquifer system and the regional groundwater basin to better quantify river aquifer exchange and to develop strategies to enhance fall flows and restore Chinook salmon fall runs. The results of this project and other information including documentation will be available on a web page in the near future.

1. Introduction

The Cosumnes River has historically supported large fall runs of Chinook salmon (TNC, 1997). Declines in fish counts over the last four decades have been linked to decreasing fall flows in the river (TNC, 1997), which are in turn linked to groundwater-surface water (river aquifer) interactions. Severe groundwater overdraft in the lower basin has resulted in a decline of groundwater levels of up to 30 feet in the vicinity of the river between 1984 and 1995 (PWA, 1997). A suite of investigations was started in October 1999 to assess the role of groundwater surface water interactions in the decline of fall flows in the lower Cosumnes Basin. Investigations included local scale field measurements to describe and quantify local exchange between the river and aquifer as well as numerical modeling of regional groundwater flow and surface water flows. Main goals of these investigations were to better understand the role of groundwater surface water interactions in the decline of Cosumnes River flows and to explore strategies that could enhance fall river flows to promote Chinook salmon fall runs. Spatial focus of this work was on the river reaches downstream of USGS gauge Michigan Bar (MHB / USGS-11335000) (Figure 1). These reaches stretch from the confluence with the Mokelumne River at Thornton Bridge (THB / river mile 0) to MHB at river mile 36. A second gauge, McConnel (MCC / USGS- 11336000), is located at Highway 99 around river mile 11 (Figure 1). Major tributaries to the lower Cosumnes are Deer Creek and Laguna Creek (Figure 1). Folsom South Canal (FSC) crosses the River at approximately river mile 24.

This report summarizes the outcome of these investigations and lays out conclusions that can be drawn from the findings. First an analysis of historical hydrologic data to assess historical trends in groundwater levels and river flows will be presented. Aim of this analysis was to explore potential causal links between groundwater and surface water development in Sacramento County and along the lower Cosumnes in particular. The current local and regional scale groundwater conditions in the lower Cosumnes Basin will be evaluated in the subsequent section. This assessment is based on field investigations that have been carried out over the last two years and on analyses of existing groundwater data and reports. Regional scenario simulations of groundwater flow will be presented that address various measures to enhance fall flows on the Cosumnes River and to recover regional groundwater levels. Surface water simulations are also presented that examine alternatives for enhancing or creating flows in the channel during specified times during fall flows. These scenarios are to be seen as exploratory tools rather than as explicit suggestions for remedial action.

2. Historical analysis of river flows and groundwater in the lower Cosumnes basin

The larger rivers draining the western side of the Sierra Nevada have naturally been intermittent to perennial rivers. Construction of reservoirs and other anthropogenic changes have profoundly changed flow patterns on most of these rivers. The Cosumnes river is the last major undammed river draining the western slope of the Sierra Nevada which has sustained a somewhat natural flow regime with large flow peaks in the Winter and very low flows in the summer. Historical flow data from the MHB and MCC gauges on the Cosumnes River (a record of flow exists for both gauges for the time period 1941-1982), however, suggests that flow volumes in the lower basin have steadily decreased. Figure 2 shows the difference in the number of days per year with flows below 10 cfs between MHB and MCC. Despite no apparent increase or decline of annual precipitation in the lower basin, the number of days per year with average daily flows below 10 cfs at MCC (downstream) has increased more than at MHB (upstream) over the 1941-82 period. This trend is even more pronounced for October flows (Figure 3), indicating that flow losses between the two gauges have increased. These losses have been linked to decreasing baseflows and the overall decline of groundwater levels. An unequivocal proof of this causal relationship for the Cosumnes River is somewhat difficult due to limited long term historical records on groundwater levels in Sacramento County. Maps of groundwater levels in Sacramento County based on well data from the Department of Water Resources (DWR) suggest that groundwater levels along extended reaches of the lower Cosumnes have been below the channel elevation for at least the last 30 years. Longer term historical groundwater records from individual wells, however, show a substantial decline of groundwater levels between 1940 and 1980 (Figure 4). This trend coincides with the increase of flow losses over the same time.

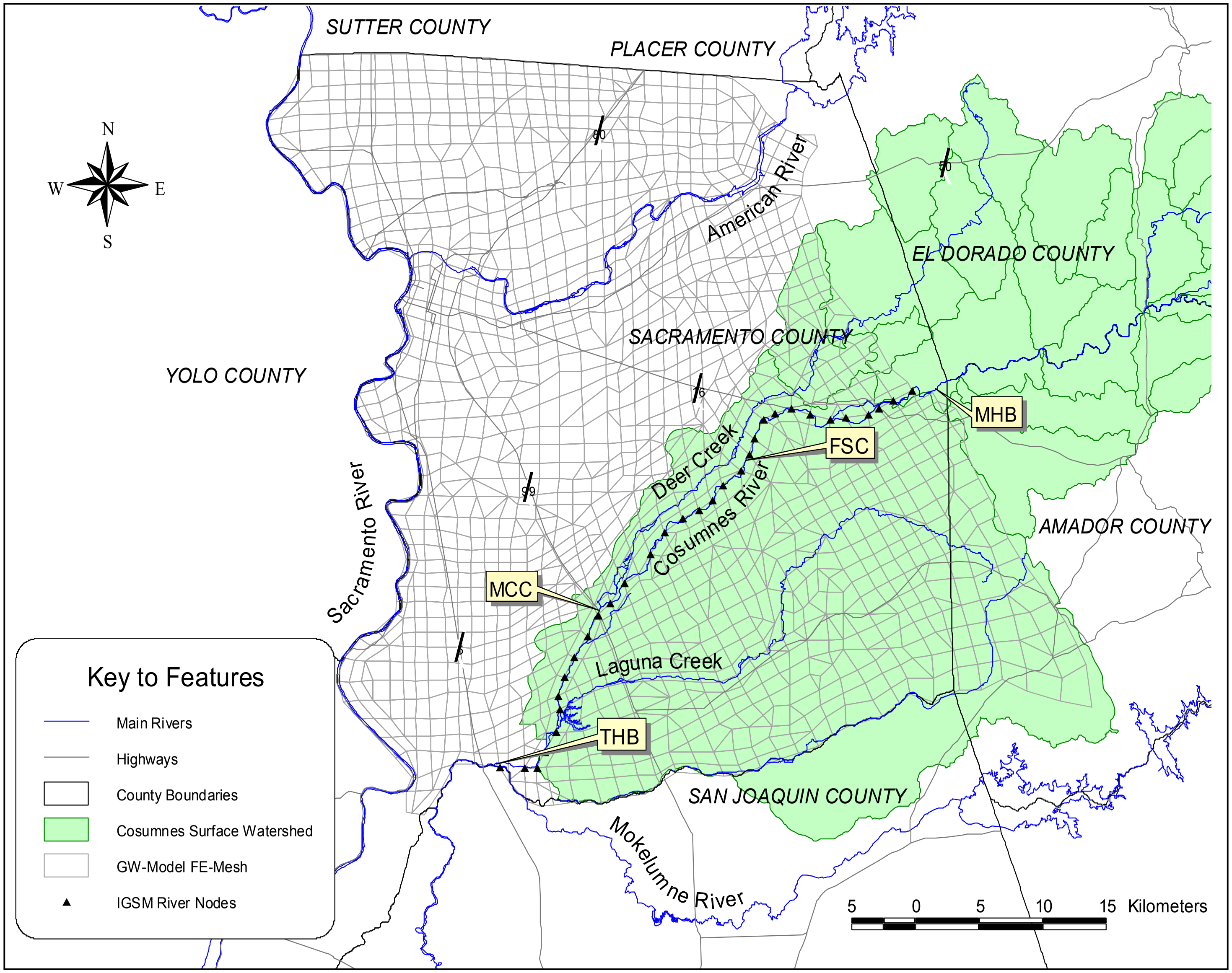


Figure 1. *Location Map and spatial extend of regional groundwater model.*

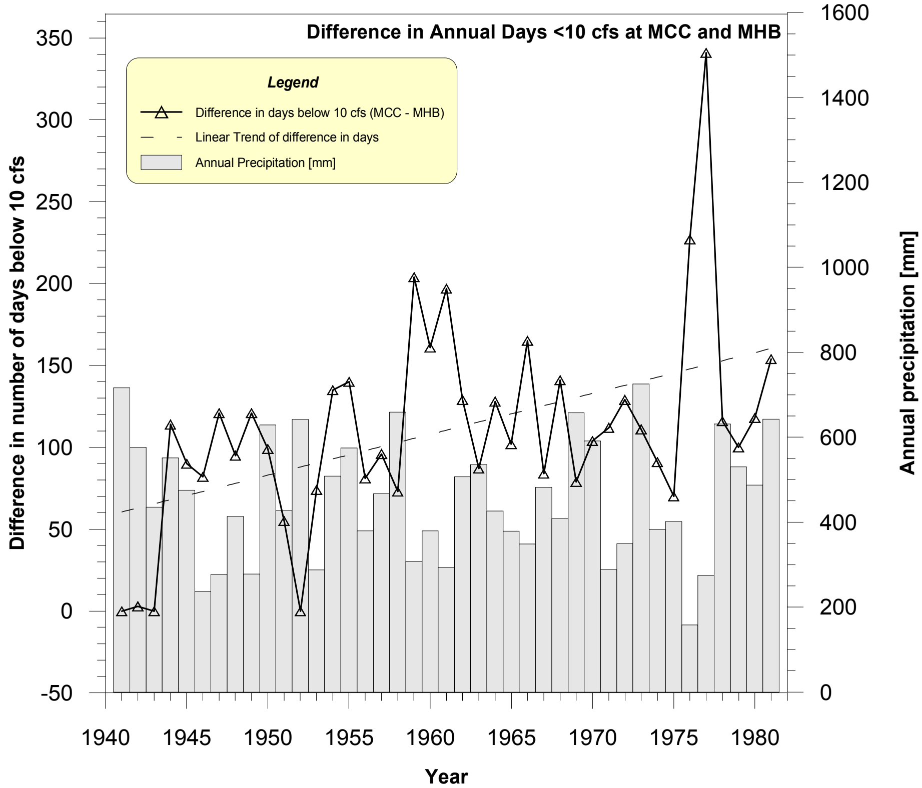


Figure 2. *Difference in number of days per year with flow below 10 cfs between the Michigan Bar (upstream) and McConnel (downstream) gauges.*

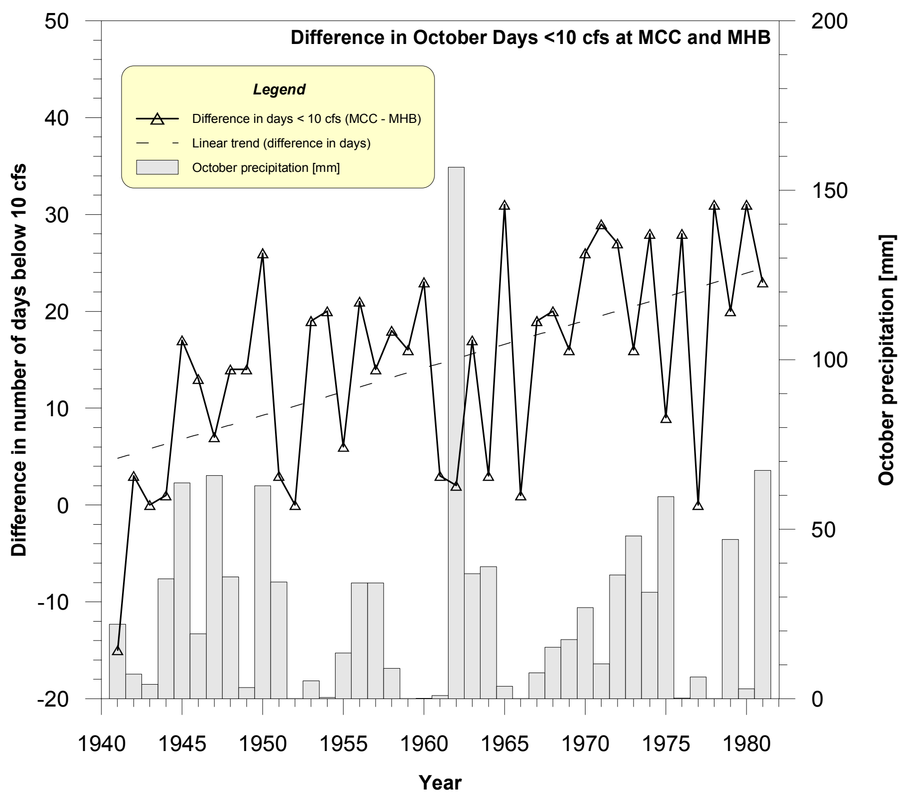


Figure 3. *Difference in number of days in October with flow below 10 cfs between the Michigan Bar (upstream) and McConnell (downstream) gauges.*

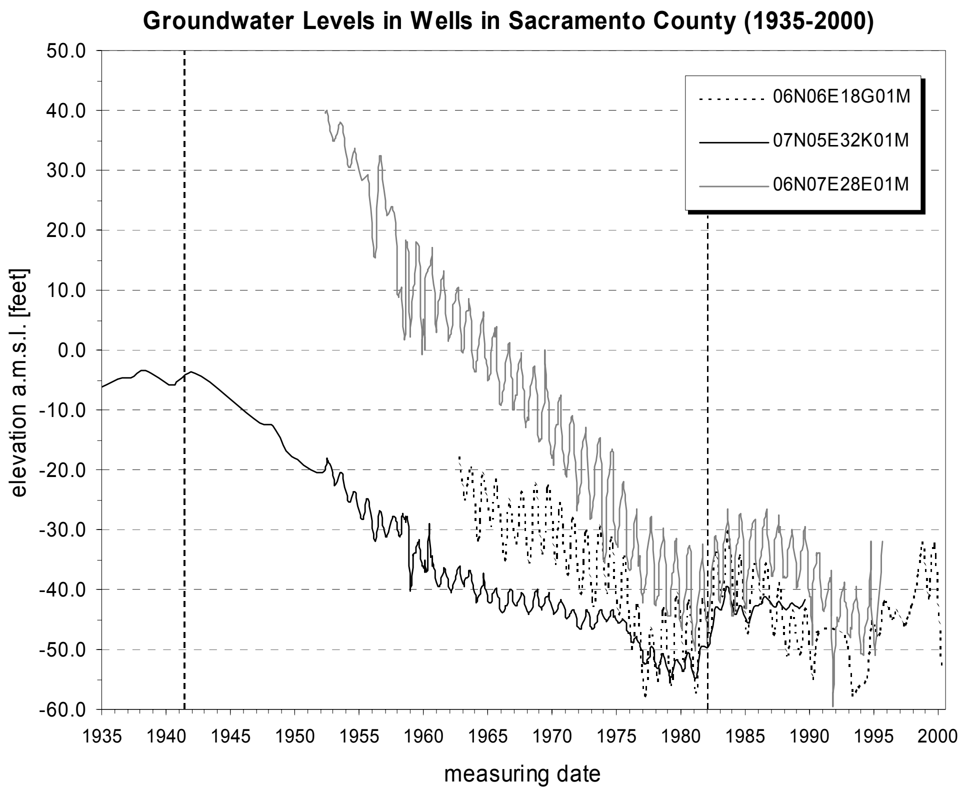


Figure 4. *Historical groundwater levels in three wells in Sacramento County.*

Well 07N05E32K01M in Figure 4 is located 12 kilometers north-west of the Cosumnes channel at Highway 99, well 06N07E28E01M about 9 kilometers south-east of the river whereas well 06N06E18G01M lies within 2.5 kilometers of the channel. If we take the historical water level decline in the first two wells as a reference to extrapolate water levels of well 06N06E18G01M backward in time, water levels in that well in the early 1940s may have been around the current river channel elevation at Highway 99 (~22 ft a.m.s.l.). That suggests that the river may have been in hydraulic contact with the regional aquifer at that time and that diminishing baseflows are at least partially responsible for diminishing river flows.

3. Current regional and local scale groundwater conditions

Current groundwater conditions in southern Sacramento County are characterized by two major cones of depression in the groundwater levels (Figure 5). The Cosumnes River is situated between these cones, the Elk Grove cone to the north and the Galt cone to the south and constitutes a source for groundwater recharge. Thirty-three groundwater wells in the vicinity of the Cosumnes River were monitored every two weeks since April 2000. These data indicate that most of the lower Cosumnes river is currently hydraulically disconnected from the regional aquifer (Appendix I). This means that along most reaches river water flows downward into the groundwater system, not vice versa, and that further lowering of groundwater levels adjacent to these reaches will not cause further increases in the rate of channel loss.. Depth to the regional water table from the river channel elevation steadily increases from 7-20 ft in the Dillard Road area (river mile 27.5) to 35-55 ft around Wilton Road (river mile 17.3). Between Wilton road and Highway 99 (river mile 11) depth to the water table decreases to 15-30 ft and reaches values of 3-15 ft around Twin Cities Road (river mile 5). Data from shallow piezometers downstream of Twin Cities Road suggests that the water table lies above the channel elevation in the lowest reaches of the river. Seasonal water table fluctuations in the monitored wells ranged from 10-17 ft. Under these conditions most of the lower river does not receive baseflow contribtions from the regional aquifer except for reaches upstream of Dillard Road and downstream of Twin Cities Road, where baseflow may seasonally and in the lowest reaches even permanently feed the river. Lowering groundwater levels in these sensitive areas could further decrease Coumnes river flows. To restore and sustain baseflows along the entire lower river water table elevations between Dillard and Twin Cities Roads would have to be raised by up to 55 ft.

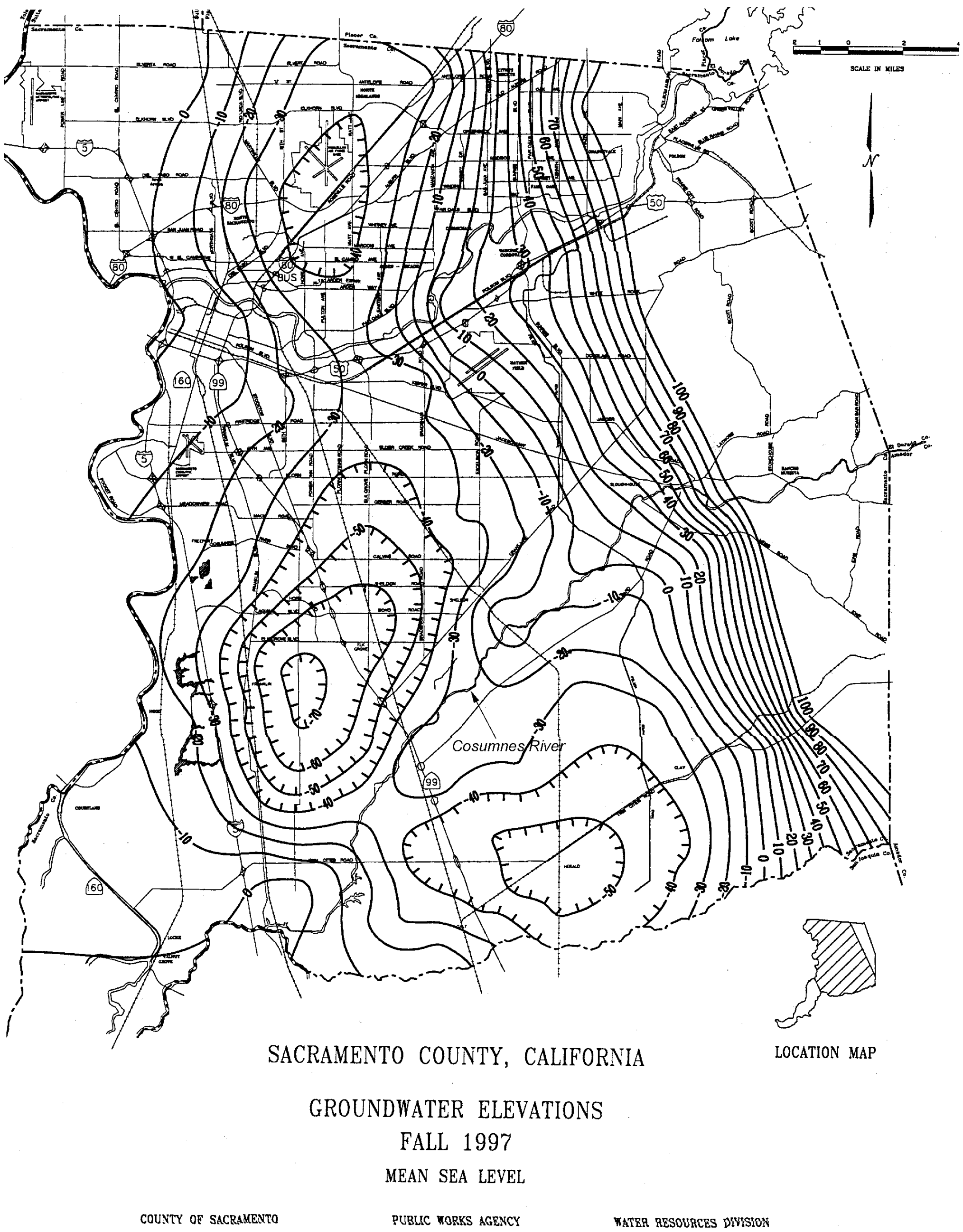


Figure 5. *Groundwater levels in Sacramento County for fall 1997.*

4. The regional groundwater model

The numerical groundwater model that was used in this study is the Integrated Groundwater Surface Water Model (IGSM) Version 3.1 (Montgomery Watson, 1993a). An IGSM based model for Sacramento County had been made available to us by the Sacramento County Water Agency (SCWA) in late 1999 and first simulations had been carried out in 2000. (See annual report from September 2000). The development of the original Sacramento County model (SCM) is described in Montgomery Watson (1993b). A description of the general structure and routines of the model used for our first simulations is given in the annual report from September 2000. Since then updates of input data to cover the period 1990-1995 have been prepared by Montgomery Watson and Navigant consultants for an extended group of users and have been made available to us in 2001 (Jonathan Goetz / Montgomery Watson, personal communications 2001). The new data were incorporated into the existing model. In the updated model, most heads for the general head boundaries, which had originally been supplied from the Central Valley Groundwater Surface Water Model (CVGSM), are now simulated simultaneously with the North American River IGSM to the north and the San Joaquin County IGSM to the south. General heads in the west are still taken from CVGSM. The number of sub-regions specified in the model domain has changed from 31 to 35. All additional sub-regions lie north of the American River so that sub-regions in the vicinity of the Cosumnes River remained unchanged (Figure 6). We implemented further changes in the model. Based on field data and a report by the USGS (Guay, 1998), river channel elevations for the Cosumnes River were corrected downward. The mesh geometry in the model was slightly changed so that stream nodes better reflect the course of the lower Cosumnes River. The final model was run over the time period 1969-1995 and simulated groundwater levels were compared to observed levels at 67 wells throughout Sacramento County. Simulated groundwater levels were found to be in reasonable agreement with the observed values (Appendix II). Simulated mean monthly river flows on the Cosumnes River at MCC also matched observed flows fairly well.

Last year an independent review of the IGSM source code (Dr. Eric M. LaBolle, personal communication 2000) had revealed limitations of the code in handling non-linear groundwater surface water interactions and demonstrated through benchmark testing against a standard code that application of IGSM can be error prone. These errors will manifest most significantly in the case of (or in transition from or to) direct hydraulic contact between the stream and aquifer and in time steps over which stream flows or groundwater heads change drastically. As most of the simulations presented here address a hydraulically disconnected system and groundwater head changes in the months of concern (fall months) are gradual, we do not believe that these limitations of IGSM affect the general conclusions drawn from our simulation results. The SCM has been fairly successful in addressing the large scale and more general questions addressed in this study. However, absolute values of simulated river flow under conditions of hydraulic connection should be viewed with caution. Design of a more reliable regional model is needed in future work.

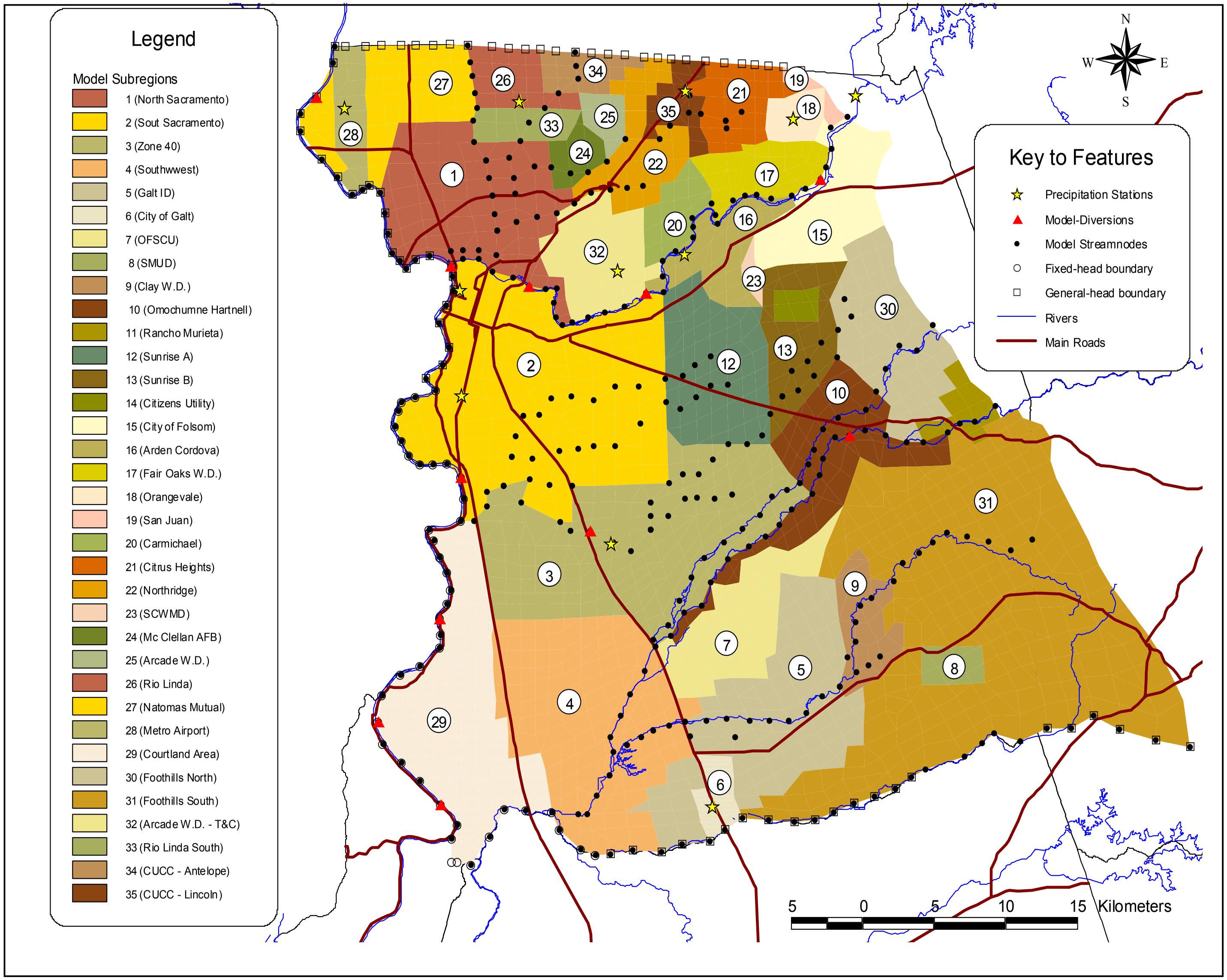


Figure 6. *Sub-region division in the regional groundwater model.*

1.1. Additional scenario simulations

Monitoring of groundwater levels in the vicinity of the Cosumnes River has shown the hydraulic disconnection between river and aquifer and the substantially reduced baseflow under current conditions. Accordingly, one goal of the scenario simulations was to assess measures for recovering regional groundwater levels and restoring baseflows. To evaluate current conditions a so-called "baseline" simulation with the most recent available data was carried out. To estimate the amount of water needed to recover regional groundwater levels and potentially restore baseflows, various scenarios with reduced pumping were simulated. To further mimic pre-development conditions as a reference for restoration, a "no pumping" scenario was simulated. As large reductions in pumping are unlikely to occur because of increasing water demands in the south county (Montgomery Watson 1997), alternative scenarios were assessed that explore possibilities to recover groundwater levels or directly restore river flows without the need for large pumping reductions. The general approach taken in these simulations is to hold constant land use, groundwater pumping and surface water diversions from year to year. Intra-annual patterns of these quantities for baseline conditions are provided by the most recent available data, namely 1994 levels of surface water diversions and groundwater pumping and the 1993 land use survey. Scenario simulations represent various degrees of perturbation to these baseline patterns. Rainfall and river inflows into the model domain for all simulations are taken from historical records to mimic "real" conditions. All simulations were run over a 15-year period, with 1980-1995 being chosen as the historical record. This time period includes dry, average and wet hydrologic years (Figure 7). Initial conditions are taken from September 1995, the end of the 1969-1995 calibration period. The neighboring regional groundwater models (North American River Model and San Joaquin County model) which provide most of the general head boundaries to the SCM are run under similar baseline conditions throughout all simulations. Table 1 summarizes all baseline and scenario simulations.

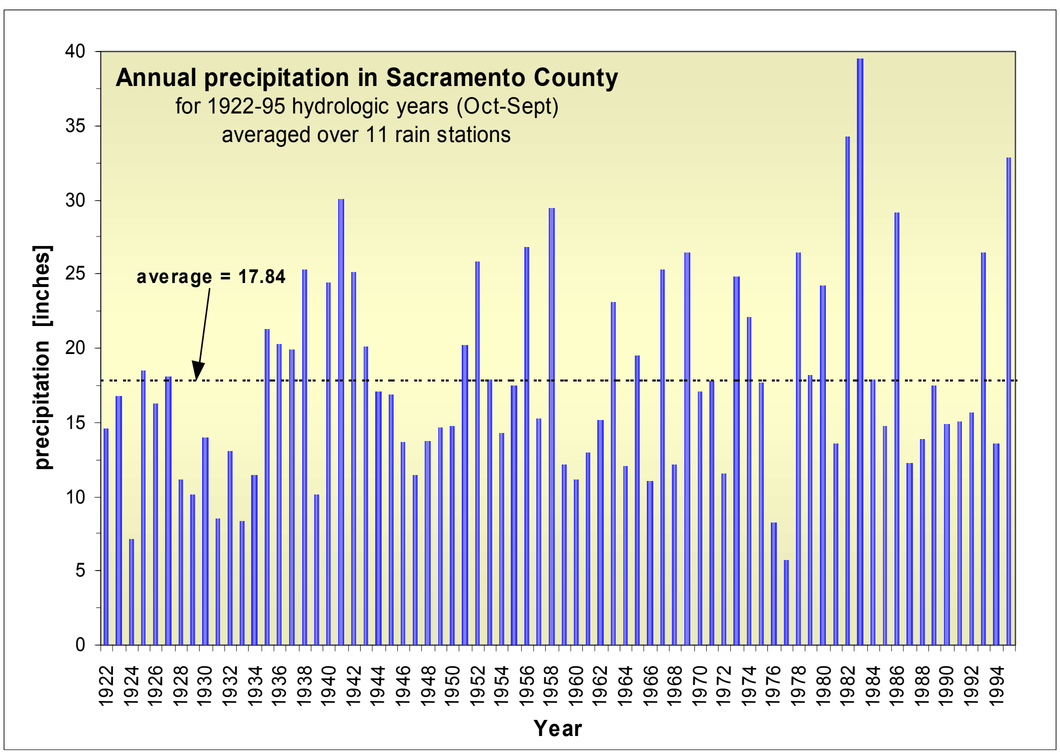


Figure 7. *Average annual precipitation in Sacramento County.*

Table 1. *Variables and parameters of simulation runs.*

	Parameter / variable	Baseline	No Pumping	Scenario 1
general	**Simulation period**	15 years	15 years	15 years
general	**Initial conditions**	1995 fall GW levels	1995 fall GW levels	1995 fall GW levels
Static in time	**Landuse**	1993 land use survey	1993 land use survey	1993 land use survey
Static in time	**GW pumpage** (time variant within year)	1994 pump rates	No pumping in all 35 sub-regions of model	1994 pump rates
Static in time	**SW-diversions & imports** (time variant within year)	1994 diversions & imports	1994 diversions & imports	1994 diversions & imports plus 50 cfs flow augmentation from FSC from Sept. to Dec.
Static in time	**Additional water needed** (per year)	None	~ 570,000 ac-ft	~ 12,000 ac-ft
time variant	**Stream/River inflows**	1980-95 record	1980-95 record	1980-95 record
time variant	**Precipitation input**	1980-95 record	1980-95 record	1980-95 record
time variant	**Boundary Conditions**	provided by simultaneous model runs from bordering groundwater models (North American River & San Joaquin County models)	provided by simultaneous model runs from bordering groundwater models (North American River & San Joaquin County models)	provided by simultaneous model runs from bordering groundwater models (North American River & San Joaquin County models)

	Parameter / variable	Scenario 2A	Scenario 2B	Scenario 3
general	**Simulation period**	15 years	15 years	15 years
general	**Initial conditions**	1995 fall GW levels	1995 fall GW levels	1995 fall GW levels
Static in time	**Landuse**	1993 land use survey	1993 land use survey	1993 land use survey
Static in time	**GW pumpage** (time variant within year)	Pumping reduced by 166,000 ac-ft with emphasis on upstream reaches (sub-regions 3,7,10,11,13,30,31)	Pumping reduced by 250,000 ac-ft with emphasis on downstream reaches (sub-regions 2,4,5,6,7)	Pumping reduced by 166,000 ac-ft with emphasis on upstream reaches (sub-regions 3,7,10,11,13,30,31)
Static in time	**SW-diversions & imports** (time variant within year)	1994 diversions & imports	1994 diversions & imports	1994 diversions & imports plus 50 cfs flow augmentation from FSC from Sept. to Dec.
Static in time	**Additional water needed** (per year)	~ 166,000 ac-ft	~ 250,000 ac-ft	~ 178,000 ac-ft
time variant	**Stream/River inflows**	1980-95 record	1980-95 record	1980-95 record
time variant	**Precipitation input**	1980-95 record	1980-95 record	1980-95 record
time variant	**Boundary Conditions**	provided by simultaneous model runs from bordering groundwater models (North American River & San Joaquin County models)	provided by simultaneous model runs from bordering groundwater models (North American River & San Joaquin County models)	provided by simultaneous model runs from bordering groundwater models (North American River & San Joaquin County models)

Baseline and "No Pumping" simulations

The baseline and no pumping simulations can be seen as reference points for the comparison of further scenario simulations. Baseline conditions represent the current status quo of groundwater use in the county whereas the "No Pumping" scenario establishes an idealized best case scenario or minimum impact situation with respect to regional groundwater levels. Total annual groundwater pumping in the model domain under baseline conditions (1994 levels) is approximately 570,000 ac-ft. In the "No Pumping" scenario groundwater pumping in the entire model domain is set to zero, practically representing a 570,000 ac-ft annual water shortage with respect to current water demands. Resulting groundwater levels represent quasi-pristine or natural pre-development groundwater conditions.

Flow Augmentation (Scenario 1)

Folsom South Canal (FSC) has been proposed as a source for fall flow augmentation to the Cosumnes River under critical flow conditions. FSC is ideally located, crossing the Cosumnes River at river mile 23 and has extra capacity that could potentially be used for such a purpose (Tad Berkebile, SCWA, 2001, personal communication). Effects of 50 cfs flow augmentation on river flows and seepage for the months September to December are addressed in scenario 1. The annual amount of water needed for this measure amounts to 12,000 ac-ft.

Pumping reduction (Scenario 2A and 2B)

The pumping reduction scenarios aim at roughly determining the annual amounts of water (represented here as pumping reductions) needed to partly reconnect the river channel with the regional aquifer and to restore baseflows. Alternatively, these amounts of water might be achieved through artificial recharge projects. Pumping was reduced on a sub-region basis, where scenario 2A focuses on regions around the upper river reaches in the study area and scenario 2B on the lower reaches. Reductions were chosen such that at least a partial hydraulic reconnection between river and aquifer could be achieved. Annual reductions of 166,000 ac-ft and 250,000 ac-ft were needed in scenario 2A and 2B respectively.

Flow augmentation combined with pumping reduction (Scenario 3)

Scenario 3 addresses the option of combining pumping reductions with fall flow augmentations. Flow augmentation from scenario 1 was combined with pumping reductions from scenario 2A

Ongoing restoration efforts, which have attempted to restore a quasi natural flood regime along the lower Cosumnes River by breaching levees and allowing the river to regularly inundate its floodplain, have triggered the question of potential impacts on regional groundwater. Large areas around the Cosumnes channel have been under water for several weeks during recent floods, providing additional sources for groundwater recharge and replenishment. Impacts of these floods on regional groundwater levels have not been fully addressed to date. To get a first estimate of potential effects of flooding on regional groundwater levels, two additional preliminary scenarios have been simulated. Additional recharge from areas that were inundated during the large 1997 flood was added to the model. In these first preliminary simulations it was assumed that recharge was spatially uniform over these areas and occurred at a constant rate throughout the months of January and February.

1.2. Simulation Results

To assess the efficiency of the various measures addressed in the scenario simulations, September groundwater levels in the upper aquifer along the Cosumnes channel at the end of the 15 year simulation period were plotted for all simulations. Annual seepage from the upper river reaches (MHB to MCC) and the lower reaches (MCC to THB) were compared over the 15 year simulation period to picture the temporal development of the imposed changes. Finally, impacts of the changed groundwater and surface water conditions on mean monthly fall flows at specific locations were evaluated to assess the potential efficiency of the scenarios for fall flow restoration.

Groundwater levels along the river channel

Figures 8 and 9 show fall groundwater levels (September) at the end of the 15-year simulation period for all simulations. Under baseline conditions the river channel is largely hydraulically disconnected from the regional aquifer. Simulated heads show a relatively small separation between channel bottom and groundwater levels upstream of Dillard Road, and the increasing separation downstream as observed in the field. When pumping is completely stopped (S0) groundwater levels rise above the channel elevation over the entire length of the river, supporting the hypothesis stated earlier that before larger groundwater development occurred in the County in the 1950s and 60s the Cosumnes River probably received substantial baseflow contributions from the regional aquifer. Flow augmentation (S1) from FSC raises groundwater levels below the augmentation point due to increased channel seepage from additional augmented river flow.

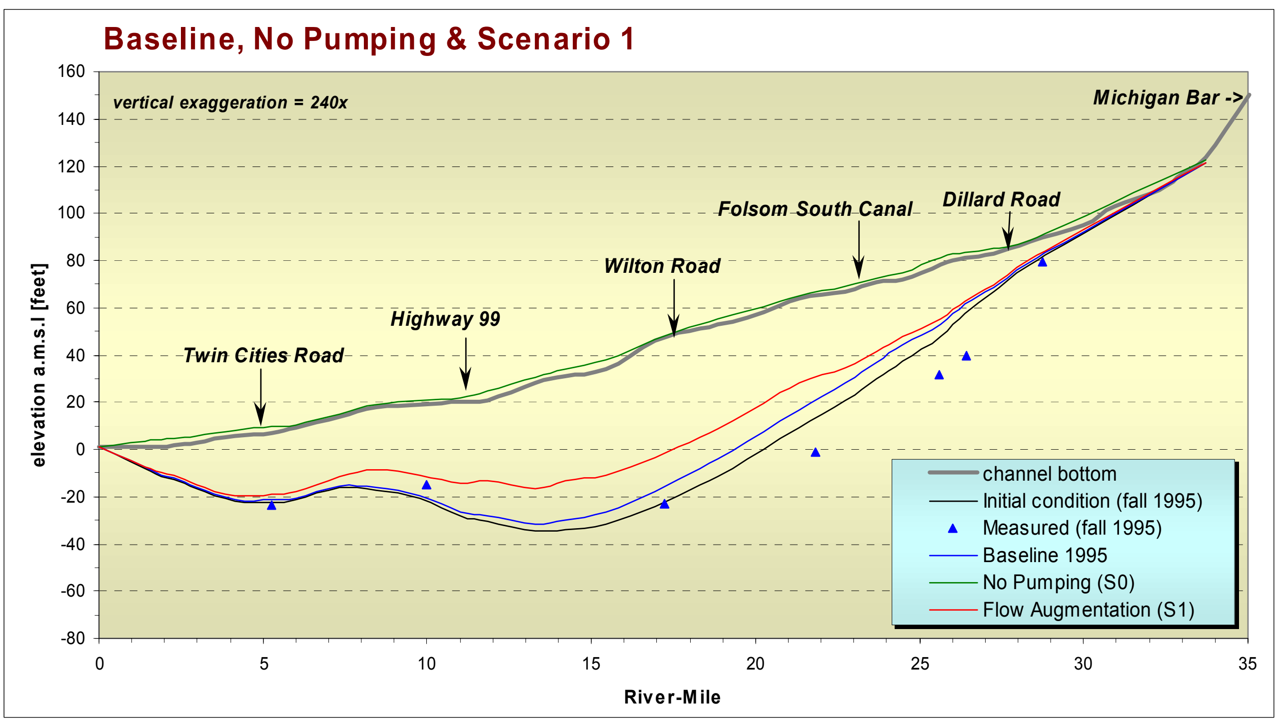


Figure 8. *Fall groundwater levels below the river channel (aquifer 1) at the end of the 15 year simulation period for baseline, no pumping and scenario 1.*

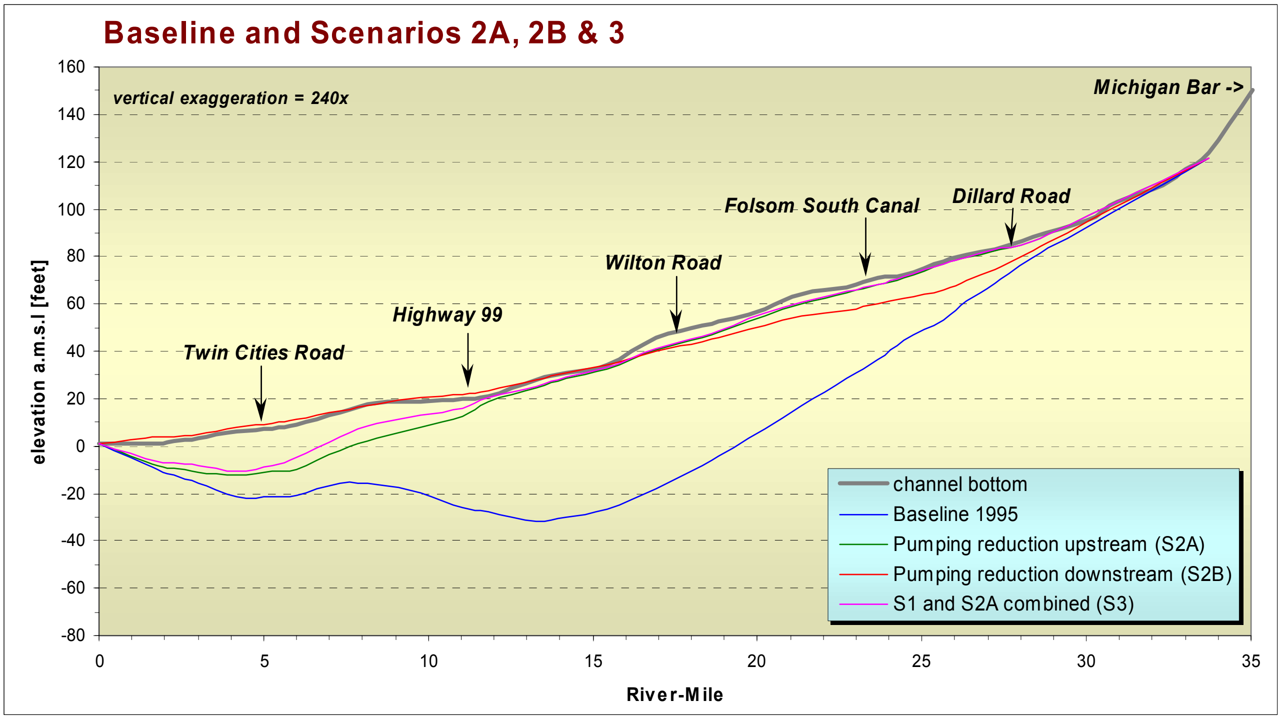


Figure 9. *Fall groundwater levels below the river channel (aquifer 1) at the end of the 15 year simulation period for scenarios 2A, 2B and 3.*

Annual pumping reductions on the order of 166,000 ac-ft were necessary to hydraulically reconnect the aquifer with the channel upstream of FSC. Even larger reductions of approximately 250,000 ac-ft were needed to establish a similar hydraulic reconnection downstream of Highway 99. In scenario 3, which combines upstream pumping reductions (S2A) with flow augementation from FSC, groundwater levels below Highway 99 increase due to increasing seepage from augmented river flows, whereas groundwater levels between FSC and Wilton Road are practically unchanged. This indicates that the river reach between FSC and Wilton Road is no longer seepage dominated under the implemented pumping reductions.

River seepage

Under baseline and flow augmentation conditions river seepage between MHB and MCC fluctuates between 39,000 and 85,000 ac-ft per year, with higher values in wetter years (higher inflows into the lower river reaches) and lower values in drier years. The same trend can be seen between MCC and Thornton Bridge (THB), where values range from 22,000 to 63,000 ac-ft. The additional water available from flow augmentation in scenario 1 increases seepage volumes slightly. Under the no pumping scenario, seepage between MHB and MCC drops below 10,000 ac-ft per year after the 7th year of the simulation. After year 12 that reach becomes a net gaining reach with baseflow contributions of up to 12,000 ac-ft per year (Figure 10A). In the no pumping scenario gaining conditions are already established after the 6th year in the lower reach (MCC to THB) (Figure 10B). Seepage from the upper reach (MHB-MCC) decreases similarly in the three pumping reduction scenarios (S2A, S2B, S3) and settles between 20,000 and 30,000 ac-ft per year after the 7th year. In the lower reach seepage volumes are only slightly reduced under upstream pumping reductions (S2B, S3). For the downstream reduction scenario (S2A) seepage volumes follow almost the same development as under no-pumping conditions.

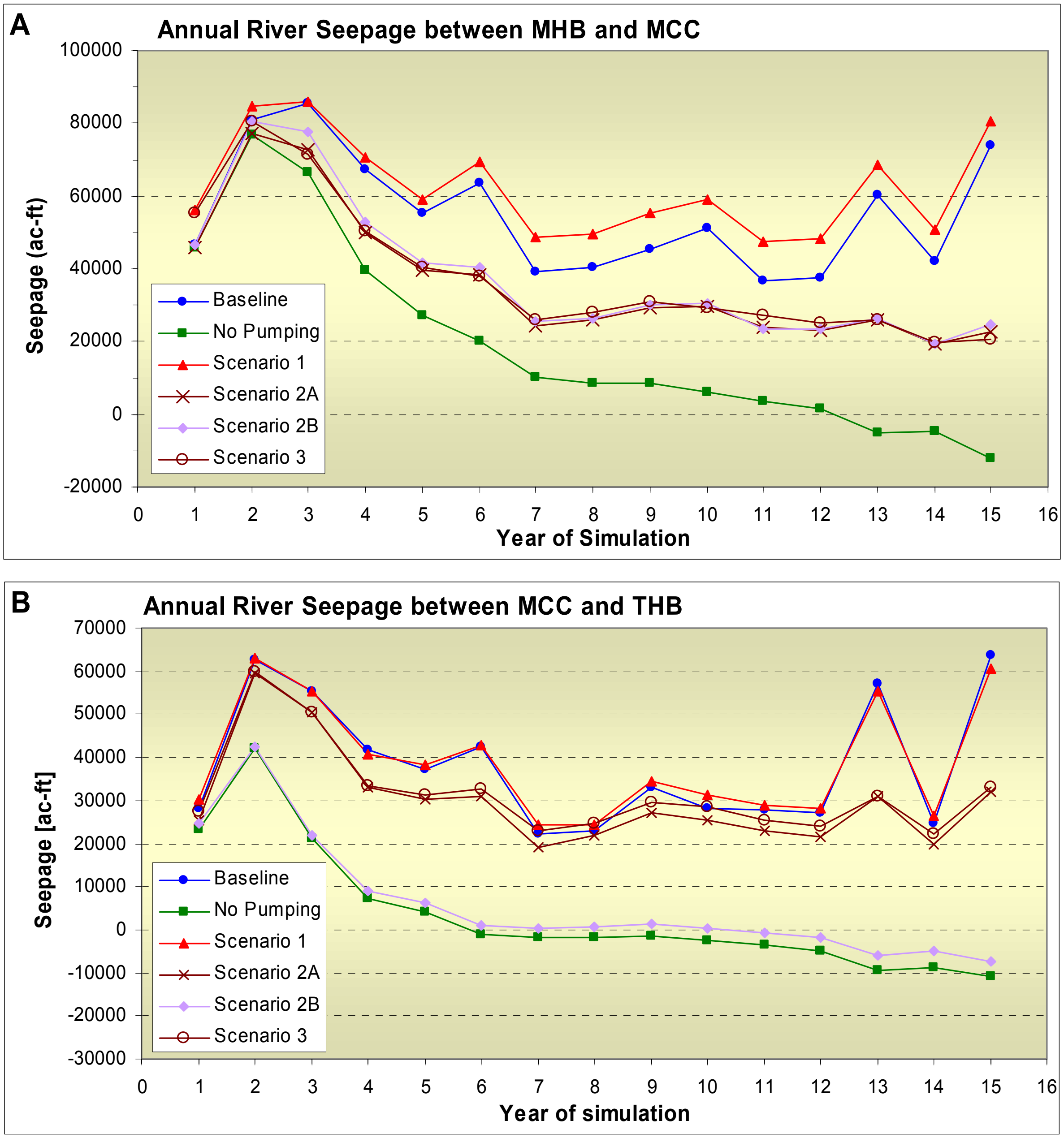


Figure 10. *Net annual seepage from the lower Cosumnes River channel between Michigan Bar (MHB) and McConnel (MCC) and MCC and Thornton Bridge (THB) for the 15 year simulation period.*

In general seepage patterns depicted in figure 10 logically follow from the simulated groundwater levels shown in figures 8 and 9. Interestingly, however, simulated annual seepage patterns suggest that the river remains a net losing river (over the course of a year the river on average loses more water to seepage than it receives from baseflow) even for scenarios where hydraulic contact is reestablished along extended reaches. Furthermore simulated seepage patterns for the "no pumping" scenario suggest that it would take longer to convert the upper portion of the river (MHB to MCC) into a net gaining reach than the lower portion (MCC to THB).

Mean monthly river flows

Potential effects of changes in groundwater levels and consequent changes in seepage from the river on fall river flows are shown in figures 11 and 12.

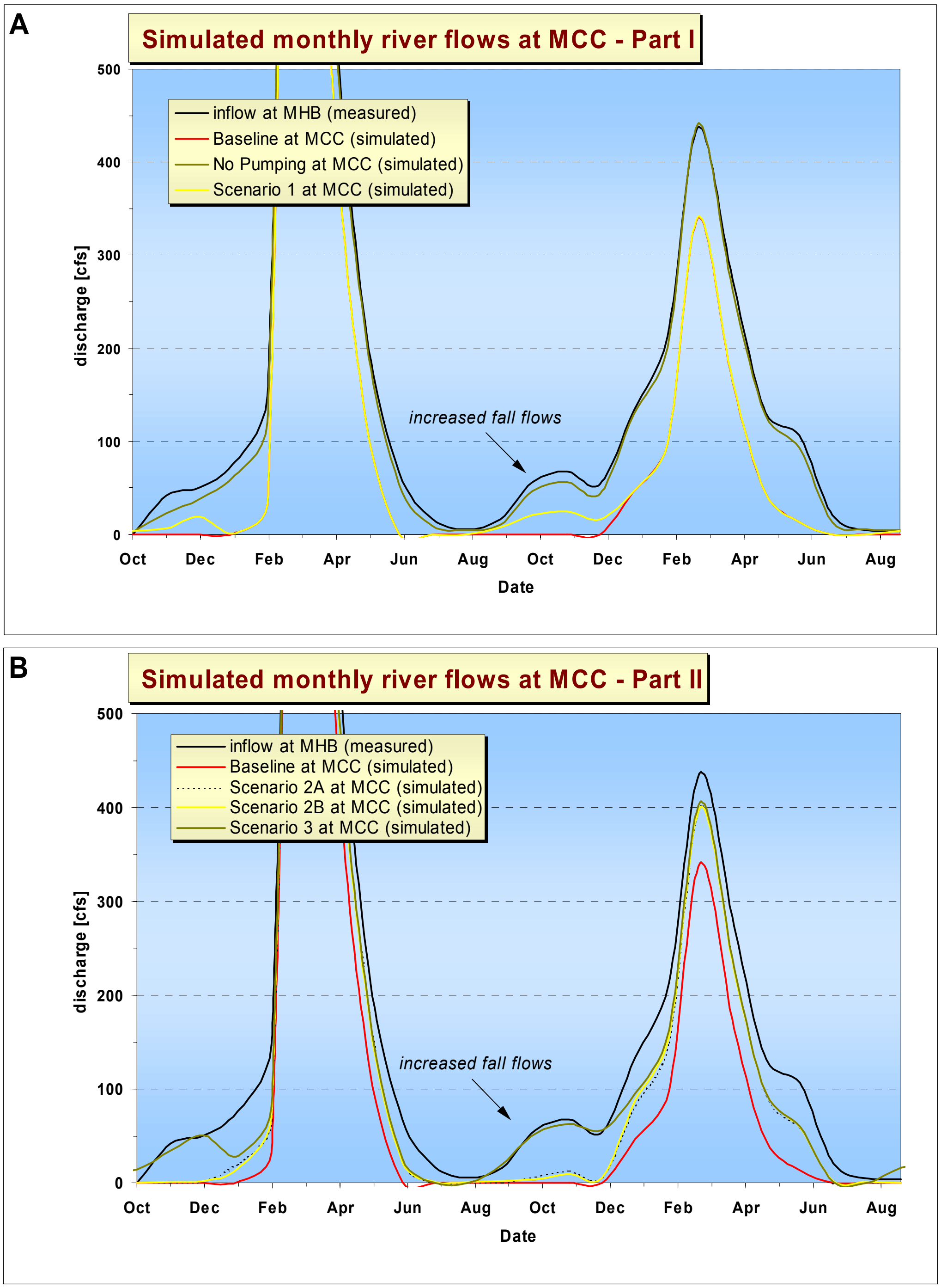


Figure 11. *Simulated mean monthly river flows at MCC for years 9 and 10 of the simulation period.*

The hydrographs show simulated mean monthly river flows on the Cosumnes River just upstream of the confluence with Deer Creek (MCC). Under baseline conditions fall inflows from MHB are almost entirely lost to seepage between MHB and MCC. For no pumping conditions, flows at MCC stay close to the upstream inflows from MHB (Figure 11A). 50 cfs flow augmentation (S1) also maintains higher flows at MCC, although on average 60% of the augmented water is lost to additional seepage. Pumping reductions and resulting decreases in seepage slightly increase fall flows similarly for upstream (S2A) and downstream (S2B) reductions (Figure 11B). Combining upstream pumping reductions with flow augmentation (S3) raises fall flows to exceed upstream inflow levels. Figure 12A provides a closer look at fall flows. The figure shows percentage of upstream October inflows from MHB, averaged over the last 10 years of the simulation period (year 5-15), that reaches various downstream points. In this figure FSC refers to the river just upstream of Folsom South Canal, where flow augmentation takes place, and MCC1 and MCC2 signify the river just upstream of the confluence with Deer Creek.

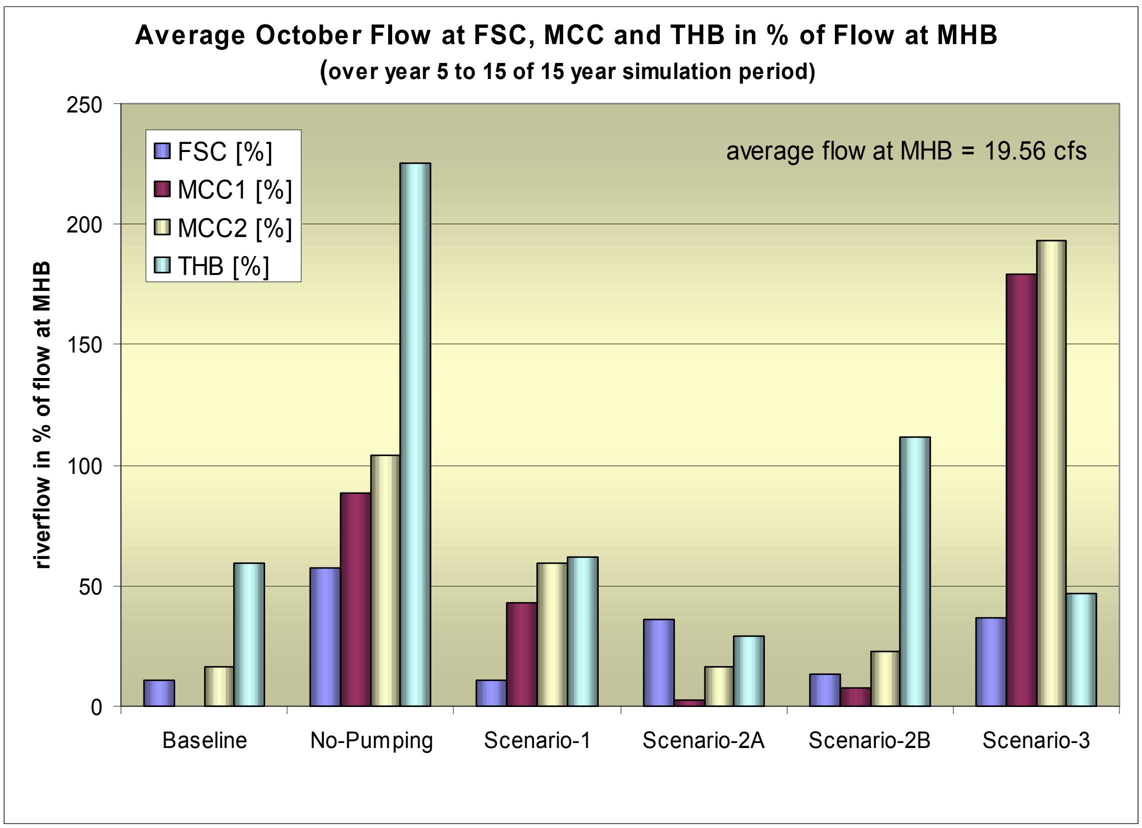


Figure 12 *Percent of MHB October flows that reach downstream points, averaged over years 5-15 of the simulation period*

These results show that under baseline conditions practically none of the simulated inflow from MHB reaches MCC. The simulations further suggest that even under no pumping conditions the river is losing water between MHB and FSC, before it receives some baseflow downstream of FSC. Sufficient flow augmentation (scenario 1) can maintain higher flows downstream of FSC despite increasing seepage losses. Upstream pumping reductions maintain higher flows at FSC but only marginally increase October flows at MCC. Downstream pumping reductions mainly benefits October flows at THB. A combination of upstream pumping reductions and flow augmentation can provide the highest October flows at MCC.

Additional recharge from inundated floodplains

Two preliminary simulations of the effects of recharge from inundated floodplains on regional groundwater levels along the Cosumnes River were carried out. Aim of these simulations was to explore additional measures that could aid the long term recovery of regional groundwater levels. The spatial extent of inundation is taken from the 1997 flood (Appendix III). In a first approximation inundation is assumed to last from January to February and recharge to be spatially uniform. All other model parameters are the same as under baseline conditions. Figure 13 shows the regional groundwater levels along the Cosumnes channel at the end of the simulation period for monthly recharge of 10mm and 100mm.

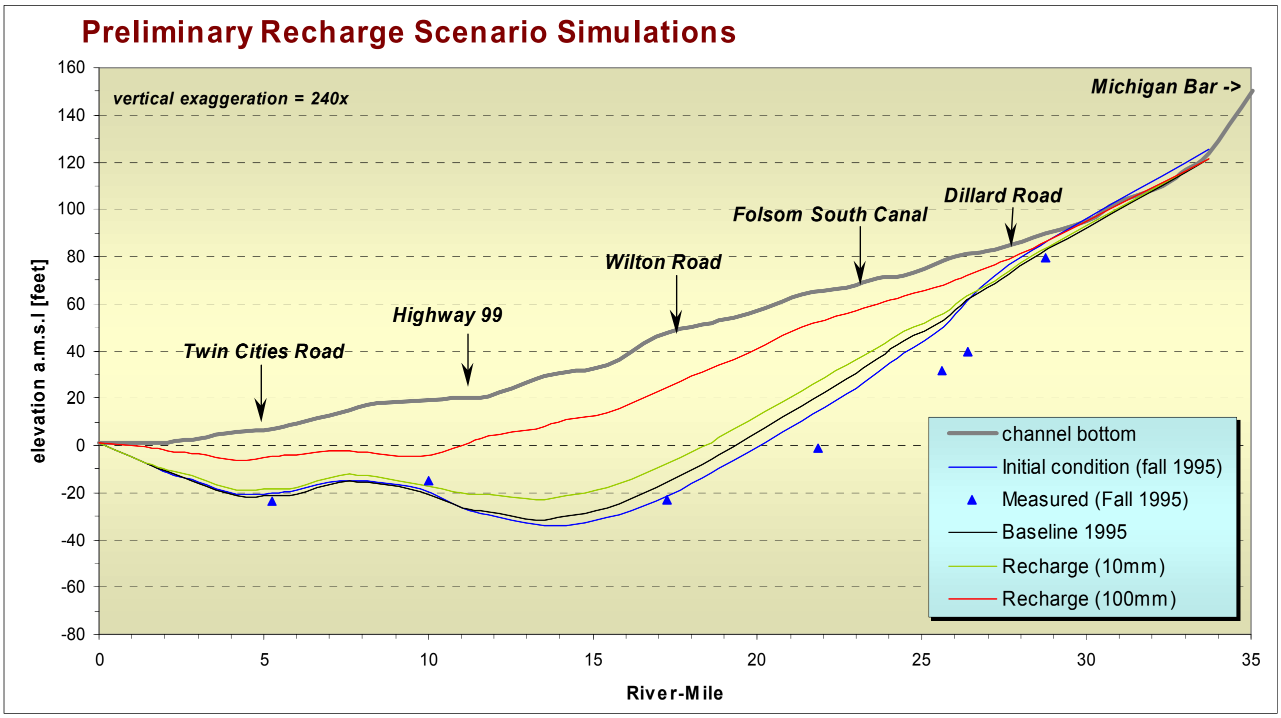


Figure 13 *Fall groundwater levels below the river channel (aquifer 1) at the end of the 15 year simulation period for 10 and 100mm monthly recharge from flooding in January and February*

Groundwater levels significantly increase in both scenarios These results are preliminary and obtained under the assumptions that all monthly recharge reaches the water table within one model time step and that recharge is uniform and steady state, both of which are gross simplifications of reality. The general reaction of the groundwater system to additional recharge from floodplains, however, suggests that large floods could significantly contribute to the recovery of regional groundwater levels.

5. Surface Water Simulations

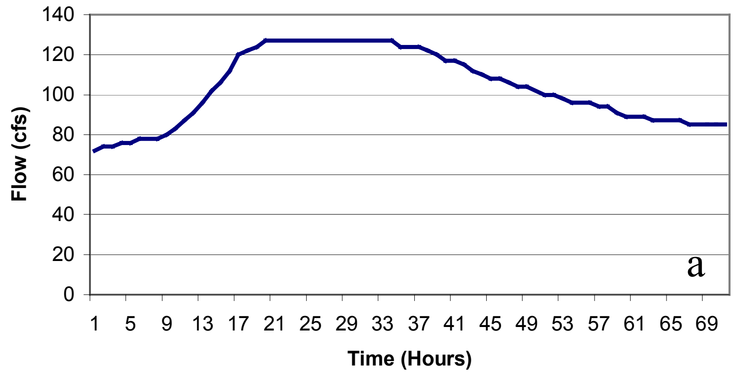
The following is an analysis of low flow conditions in the lower Cosumnes River from Michigan Bar to the McConnell stage gage. The analysis was conducted with a one-dimensional diffusion wave routing program with an infiltration component. The diffusion wave routing component of the model uses an implicit finite difference scheme with a simple trapezoidal cross section (Anderson, 1993). The infiltration routine is based upon the Green and Ampt method using a Runge Kutta solution technique. Z. Q. Chen supplied the subroutine for the Green and Ampt infiltration. The model was calibrated to a low-flow storm event of December 1999. Using the calibrated model parameters, flow conditions were analyzed for the Michigan Bar to McConnell reach to assess flow requirements at Michigan Bar to assure a 0.6 feet depth of flow at McConnell. Analysis of the last nine years of historical flow data at Michigan Bar during the time period June 30 through November 30 was made in order to determine the flow augmentations needed at Michigan Bar to assure the 0.6 feet depth of flow at McConnell based upon the model results.

5.1 Reach Characteristics

The Cosumnes River from Michigan Bar to the McConnell stage gage is approximately 25 miles in length. While actual channel geometry varies, the routing model, DIFWAVE, uses a simplified geometry with a single base width and side slope for a trapezoidal cross section. Analysis of cross-sectional data of this reach yielded an average base width of 30 feet and side slopes of 0.175 ft/ft (horizontal to vertical). The channel slope was estimated to be 0.001 ft/ft. The infiltration is modeled using five parameters: streambed saturated hydraulic conductivity and streambed thickness, aquifer saturated hydraulic conductivity, capillary suction pressure, and effective porosity. A streambed thickness of 16 inches, a capillary suction pressure of 5 inches, and an effective porosity of 0.3 were used for the simulations. Saturated hydraulic conductivity of the stream bed and underlying aquifer were estimated based on observed data supplied by Jan Fleckenstein. From this data, the streambed saturated hydraulic conductivity was estimated to be 0.252 in./hr., and aquifer saturated hydraulic conductivity was estimated to be 0.135 in./hr. Manning's roughness coefficient, n, was chosen to be the calibration parameter. Results of the calibration exercise are shown next.

5.2 Calibration

Initial calibration of the model used flow data from the Michigan Bar gage and stage data from the McConnell stage gage. Data was downloaded from the California Data Exchange Center (CDEC) for a December 1999 storm event. The inflow hydrograph for this event is shown in Fig. 14a where the maximum flow at Michigan Bar was 127 cfs. The Manning's n value was changed in order to match the depth fluctuations at McConnell. A plot of simulated versus observed stage fluctuations at McConnell is shown in Fig. 14b. The resulting Manning's n value was 0.028, The maximum error (difference between observed and modeled depths at McConnell) at any time during the simulation was 0.06 ft. Model parameters used in the low flow study are summarized in Table 2.



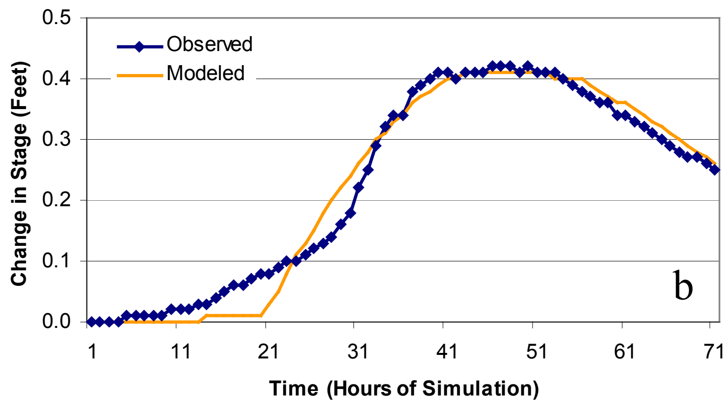


Figure 14. (a) Inflow hydrograph at Michigan Bar for calibration exercise (b) Simulated versus observed stage fluctuations at McConnell for calibration exercise.

Table 2 – Calibrated Model Parameter Values

Parameter	**Value**	**Parameter**	**Value**
Streambed Thickness	16 inches	Length	25 miles
Streambed Saturated Hydraulic Conductivity	0.135 in./hr.	Base Width	30 feet
Aquifer Saturated Hydraulic Conductivity	0.252 in./hr.	Side Slopes	.175 ft./ft.
Effective Porosity	30%	Channel Slope	0.001 ft./ft.
Pore Suction Pressure	5 inches	Manning's n	.028

5.3 Low Flow Study

The first run in this group of simulations was to determine the minimum flow needed at Michigan Bar to achieve a steady depth of 0.6 feet at the downstream node. The simulations were carried out in the following manner. Initial flows in the reach are 20 cfs. The flows are then increased one cfs/hr steadily up to 40, 43, and 45 cfs after which point the flow remains constant. The upstream hydrographs for these simulations are shown in Fig. 15a, while the downstream stage hydrographs are shown in Fig. 15b. The associated downstream flow hydrographs are shown in Fig. 15c. Fig. 16a shows the depth profiles along the 25-mile reach of river for each of the flows, while Fig. 16b shows the associated flow profiles, and Fig 16c shows the seepage profile. At 40 cfs, the downstream stage stabilizes at 0.56 feet, which is too shallow. At 45 cfs, the downstream stage reaches a steady state at 0.65 feet, which is greater than the target of 0.6 feet. At 43 cfs, the downstream stage reaches a steady state of 0.62 cfs, which is approximately equal to the target depth of 0.6 feet. From this study, it would appear that the parameters obtained from model calibration, the flow at Michigan Bar must lie between 40 cfs and 45 cfs for the depth at McConnell to reach the steady state value of 0.6 feet.

5.4 Folsom South Canal Releases

If flow augmentation were provided via Folsom South Canal – approximately 9 miles downstream of Michigan Bar – the flow requirements to reach the 0.6 ft requirement at McConnell would likely be less than those specified at Michigan Bar. In order to determine the amount of flow augmentation from Folsom South Canal, the channel length in the diffusion wave with infiltration model was changed from 25 miles to 16 miles. The remaining parameters were kept the same. Figure 17a shows the upstream hydrographs used in the simulations starting from 20 cfs and increasing to 30, 33, and 35 cfs. Fig 17b shows the associated downstream depth hydrographs and 17c shows the associated downstream flow hydrographs. As can be seen from Fig 16, the flow augmentation requirements from Folsom South Canal needed to obtain 0.6 feet of flow at McConnell lie between 30 and 35 cfs. At 30 cfs, the downstream depth reaches 0.57 ft while at 35 cfs the downstream depth reaches 0.65 ft. At 33 cfs the downstream depth is 0.62 ft.

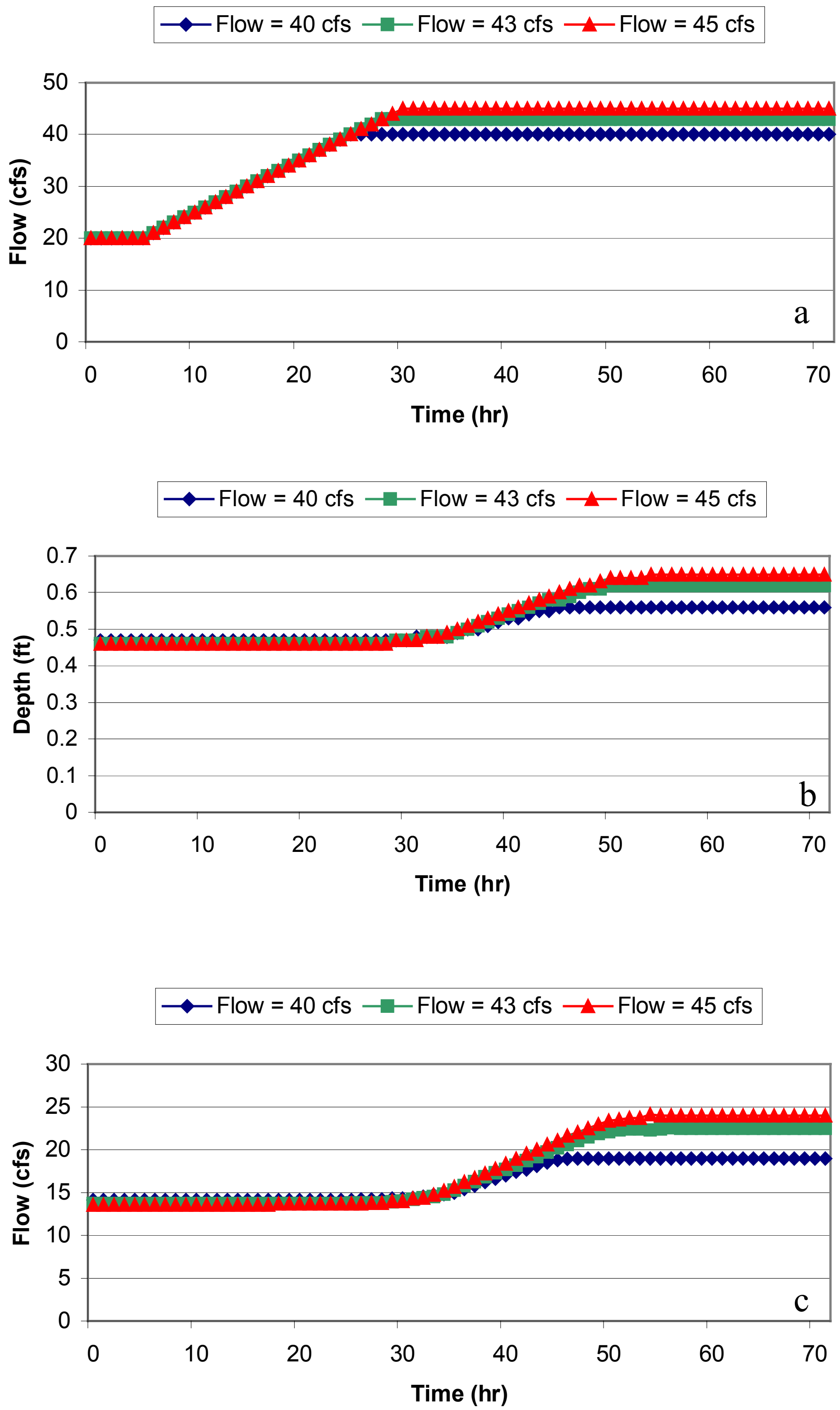


Figure 15. (a) Upstream flow hydrographs (b) Downstream stage hydrographs for different upstream flows; (c) Downstream flow hydrographs for different upstream flows.

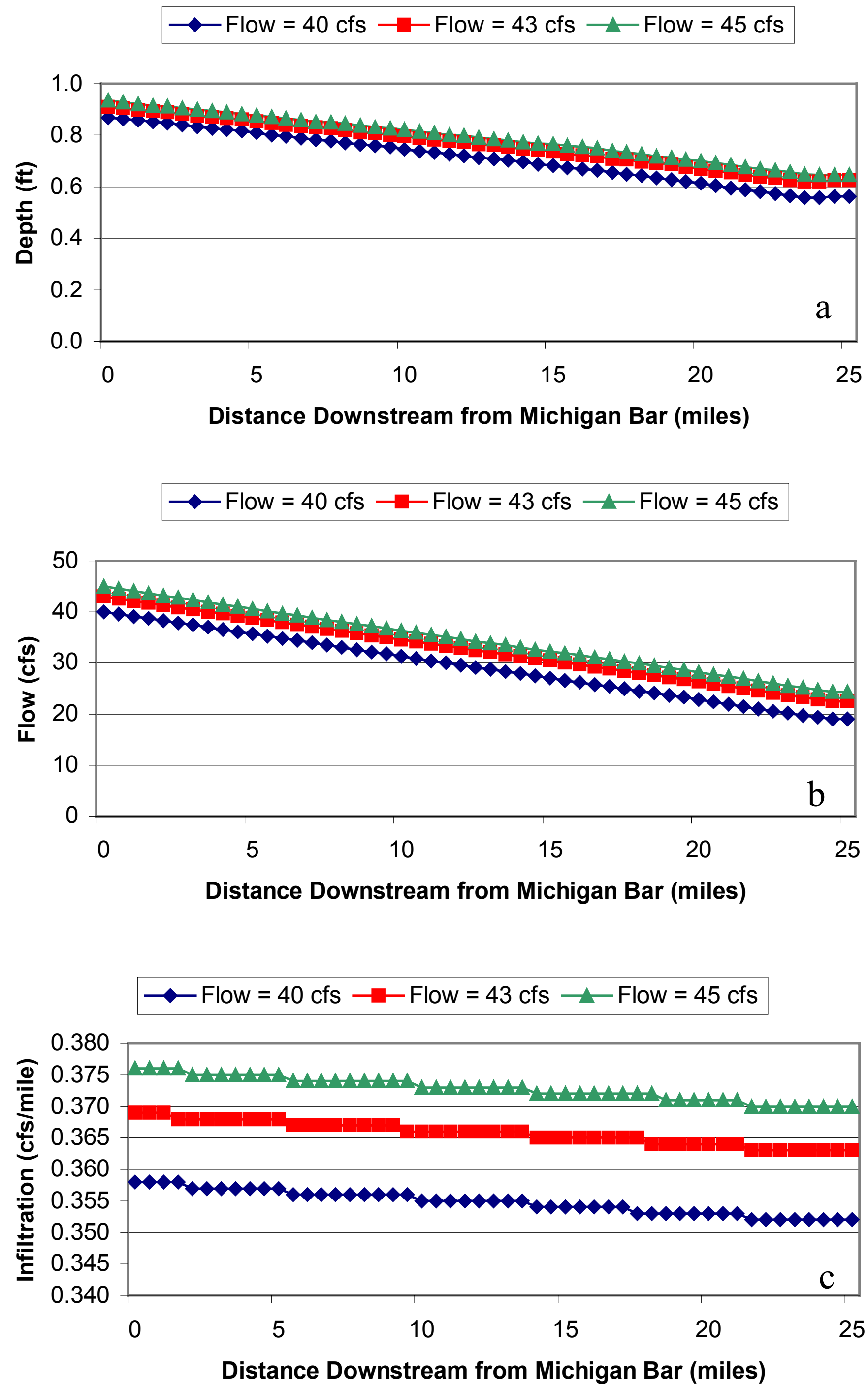


Figure 16. Depth (a), flow (b), and seepage (c) profiles along 25-mile Cosumnes River reach for different upstream flows.

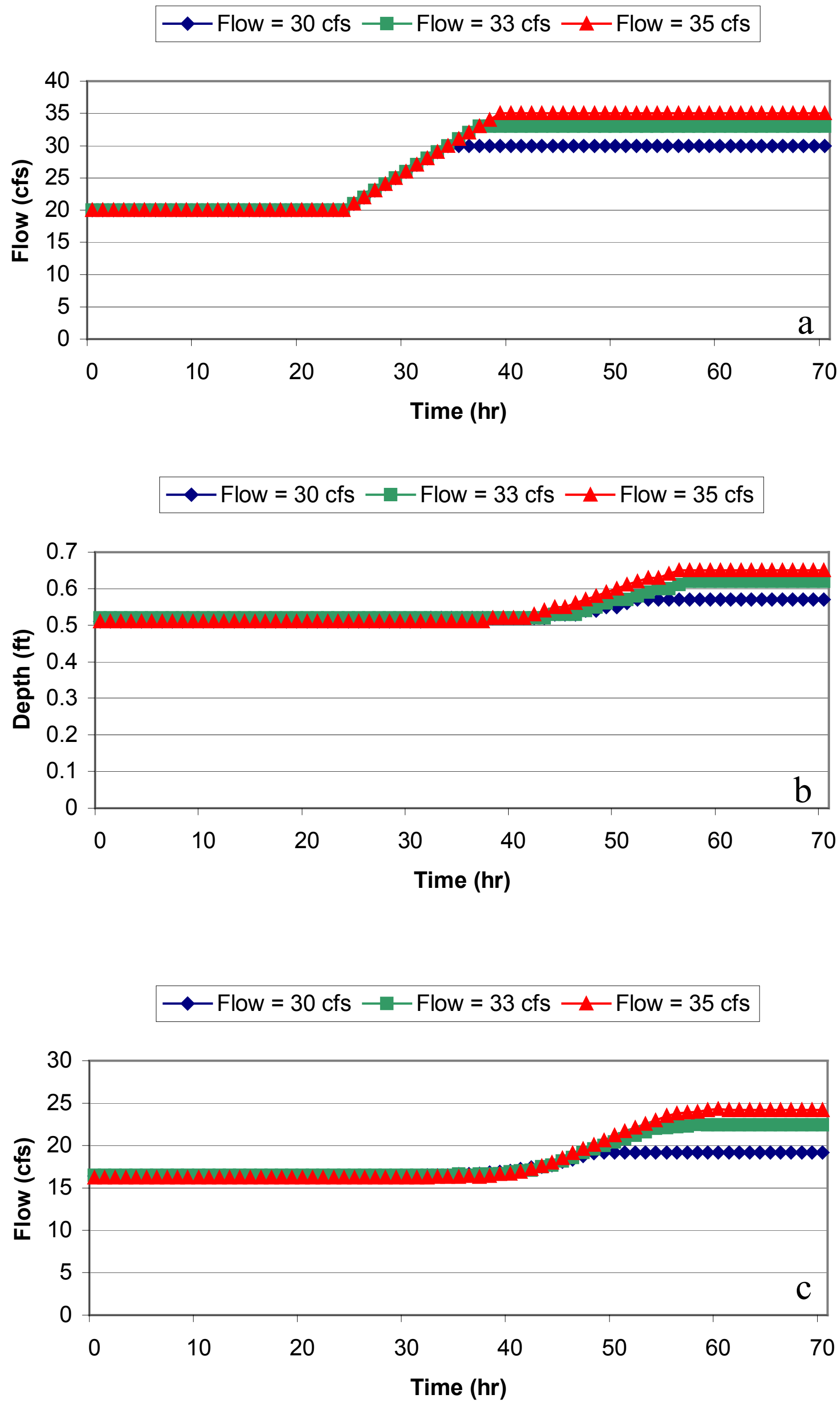


Figure 17. (a) Upstream flow hydrographs for Folsom South Canal as upstream boundary (b) Downstream stage hydrographs for different upstream flows; (c) Downstream flow hydrographs for different upstream flows.

5.5 Historical Data Analysis

Low flows in the Cosumnes River generally occur in the summer and fall seasons with minimum flows occurring in September and October. For the analysis of historical data, daily data from the USGS for the Michigan Bar gage were obtained for the months of October, November, and December. Table 3 presents the results of this analysis showing the mean volume of water necessary to augment flows to 45 cfs for each month for each water year type. The water year types are taken from the California Department of Water Resources Water Year Index classification (DWR, 1998). There are five water year types: critical, dry, below normal, above normal and wet. Figure 18 shows the mean daily flow by water year type for (a) October, (b) November, and (c) December with the 45 cfs limit highlighted. As can be seen from Fig. 18 and Table 3, some flow augmentation is required in October for all water year types. In November, flow augmentation is required only for below normal, dry and critical water year types. Note that the augmentation for the below normal category is minimal at 8 acre-ft. For December, only critically dry years require flow augmentation in the mean. The maximum volume of flow augmentation for a month is 2767 acre ft meaning that all 45 cfs is coming from the augmenting source. Note that these values are computed for the mean of the water year types computed for the observed record. There may be individual years where more water than the values in Table 4 are required such as in year 1991 when 2307 acre ft would have been needed in October, 1599 acre ft would have been needed in November, and 1586 acre-ft would have been needed in December.

Table 4 Mean monthly flow augmentation volumes for each water year classification

Water Year Classification	Critical	Dry	Below Normal	Above Normal	Wet
October Augmentation Volumes at Michigan Bar	1487	1178	1154	989	887
November Augmentation Volumes at Michigan Bar	708	49	8	0	0
December Augmentation Volumes at Michigan Bar	37	0	0	0	0

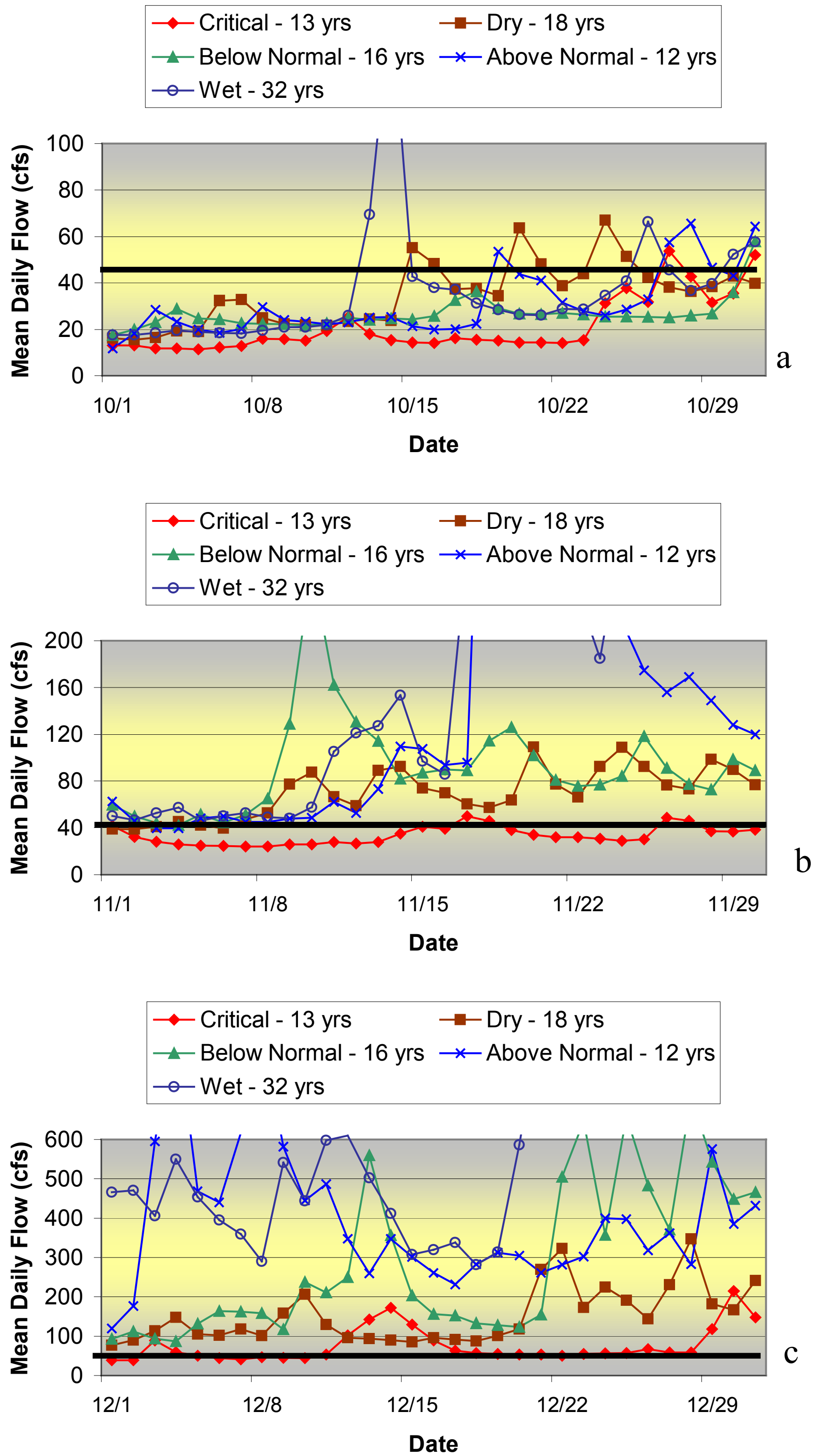


Figure 18. Mean daily flow profiles by water year type for (a) October, (b) November, and (c) December.

5.6 Re-establishing Flow from a Dry Riverbed

As an alternative to maintaining flow constantly in the channel in order to provide 0.6 feet of depth at McConnell, simulations were carried out where the river is allowed to dry up and flow is then re-established back to the 0.6 feet of depth at McConnell. For these simulations, an analytical solution to the diffusion wave routing scheme was implemented, as the computer model is not capable of having dry segments. Using the analytical solution to the diffusion wave routing method with infiltration computed using a Green and Ampt methodology, it was determined that it would take approximately 16 acre-feet of water to re-establish flow in the 13 mile reach from Folsom South Canal to McConnell. The depth profile for the re-established flow along the river reach is shown in Fig. 19 where an upstream depth of approximately 2.17 feet is required to maintain the downstream depth of 0.6 feet. Once the flow is re-established, additional water would be needed to maintain flows in the river sufficient to keep 0.6 feet of water at McConnell. For a one-month window, approximately 2767 acre-feet of water would be needed assuming no natural flows exist during this time period. This is significantly less than the volume of water required for maintaining flows sufficient to provide 0.6 feet at McConnell throughout the fall for years such as 1991 where the river ran dry. However, this smaller volume is still a significant portion of the available storage of Sly Park Reservoir (Jenkinson Lake).

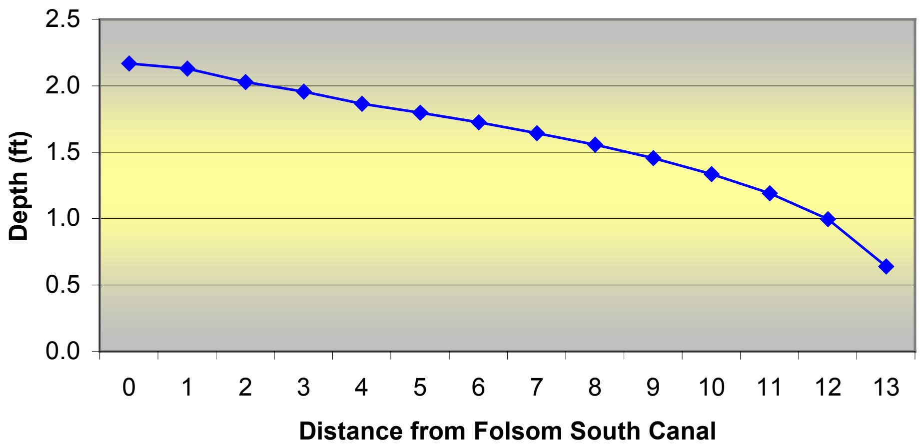


Figure 19. Depth profile of re-established flow along river reach from Folsom South Canal to McConnell obtained from analytical solution.

6. USGS Modular Modeling System Setup and Simulations

The Hydrologic Model of Cosumnes River Basin (HMCRB) under the USGS Modular Modeling System (MMS) uses a modified Precipitation-Runoff Modeling System (PRMS) to simulate daily stream flows when precipitation and temperature values are given. This model is refereed to as MMS-HMCRB thereafter in the report. The MMS-HMCRB is capable of simulating hydrologic state variables which describe the hydrologic conditions of the Cosumnes River basin in time and lumped space, i.e., flood peak discharges, fall low flows, snow accumulation, soil moisture storage, water storage in ground reservoir, etc. The model may be used to study the hydrologic conditions in Cosumnes River basin under different water use scenarios (e.g., with diversions and without diversions). MMS-HMCRB was developed to be run in Linux-based computers. It uses X-windows and Motif for its graphical user interface (GUI). The main graphics window of MMS-HMCRB is shown in Figure 20. Editing of model parameters, model calibration and simulation runs can be done interactively under the GUI of the model. MMS-HMCRB also has a geographic information system (GIS) interface which is capable of displaying the spatial distribution of model parameters and of the spatial and temporal variation of simulated state variables during a model run.

In the previous project year (1998-1999), our group had concentrated on upgrading an existing MMS-HMCRB. In this project year (1999-2000), we calibrated the MMS-HMCRB using historical data in Cosumnes River Basin and examined the model performances under different conditions.

6.1 Model Setup

The Cosumnes River Basin was divided into 39 subbasins and 83 hydrologic response units (HRUs) in MMS-HMCRB. HRUs are the basic computational elements in MMS-HMCRB (see Figure 22). MMS-HMCRB uses water storage terms in order to control the water flow between different flow processes in the basin. The seven types of storage in the model as well as the flows in between them, as shown in Figure 22, are described as follows.

Interception storage contains precipitation that is held on vegetation leaves in the basin. Interception capacity is a function of seasonal vegetation cover density in the model. Precipitation (rain, snow, or a mixture of both) falling on a HRU was determined using its elevation, the daily precipitation observed at a climate station nearby and the daily maximum and minimum air temperatures from the same station or another climatic station.

Snowpack storage represents the snow accumulation on land surface. Snowmelt from the snowpack of a HRU was determined by observed daily maximum and minimum air temperatures and the solar radiation computed using potential solar radiation and the slope/aspect values of the HRU. Evapotranspiration computation also uses the solar radiation term.

Impervious zone storage contains water on the impervious land surface such as roads. When Impervious zone storage reaches it capacity, surface runoff occurs in the model. Surface runoff was modeled as a function of antecedent soil moisture and rainfall amounts.

Soil zone storage holds water in the root zone. Infiltration, depletion, and recharge to the soil zone storage, to the subsurface storage, and to groundwater storage were related to the soil zone storage. Subsurface storage contains water between the root zone and the water table and is available for relatively rapid movement to streams in the basin. The groundwater storage is the water which generates all stream base flow. Subsurface flow occurs during, and for a period, after rainfall and snowmelt. It moves faster than groundwater. Both Subsurface flow and groundwater flow were modeled by non-linear storage routing schemes. The groundwater storage routing scheme regulates how much water from groundwater storage goes to stream reach and how much water goes to groundwater sink.

The diversion stock pond storage is the water that was stored in the stock pond before being applied to the field. Diversions were modeled using water right data and the evapotranspiration loss from irrigated lands and storage ponds. No channel routing is performed with the daily time step in the model, which is equivalent to assuming that the changes in stream storage of all reaches are zero at the daily time increment.

System inputs to MMS-HMCRB are the daily precipitation and daily maximum air temperature, and daily minimum air temperature, as shown in Figure 22. The original MMS-PRMS allows snow accumulation and solar radiation as its system inputs, but such data sets are not available in Cosumnes River Basin. The diversion data were treated as parameters of the basin, and do not vary from time to time. Therefore, they do not appear in the input file of the model. The input file of MMS-HMCRB contains observed stream flow for calibration purposes.

The major water outputs from the basin are the stream flow at the basin outlet and the evapotranspiration terms from various storages, which are shown as "ET" clouds in Figure 22. An ET term may consist of evaporation, transpiration, and/or sublimation. Groundwater sink and water exports are also accounted for as water outputs from the basin in order to balance the water quantity in the basin.

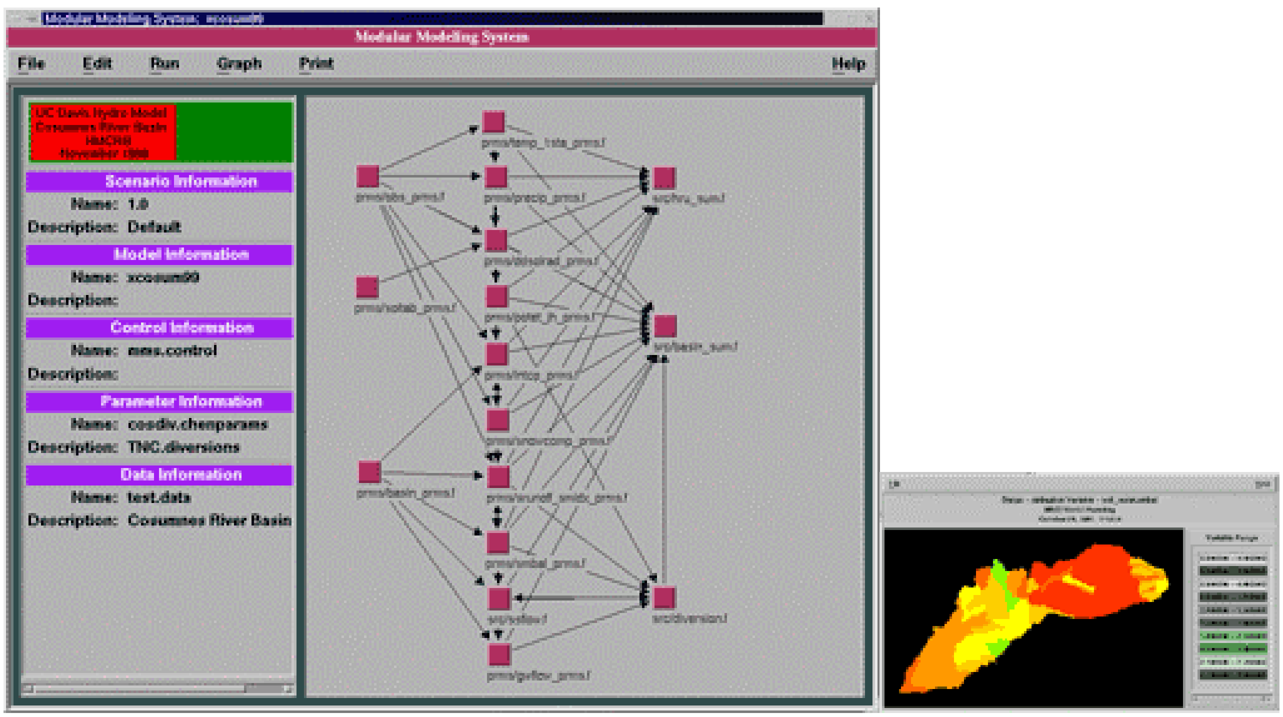


Figure 20. Graphic User Interfaces of HMCRB. The flow chart in the middle shows the modules used in the HMCRB and the data flow between modules. The window in lower right corner is a snapshot of an animation which shows the changes in the soil moisture conditions in space and time in the Cosumnes River basin.

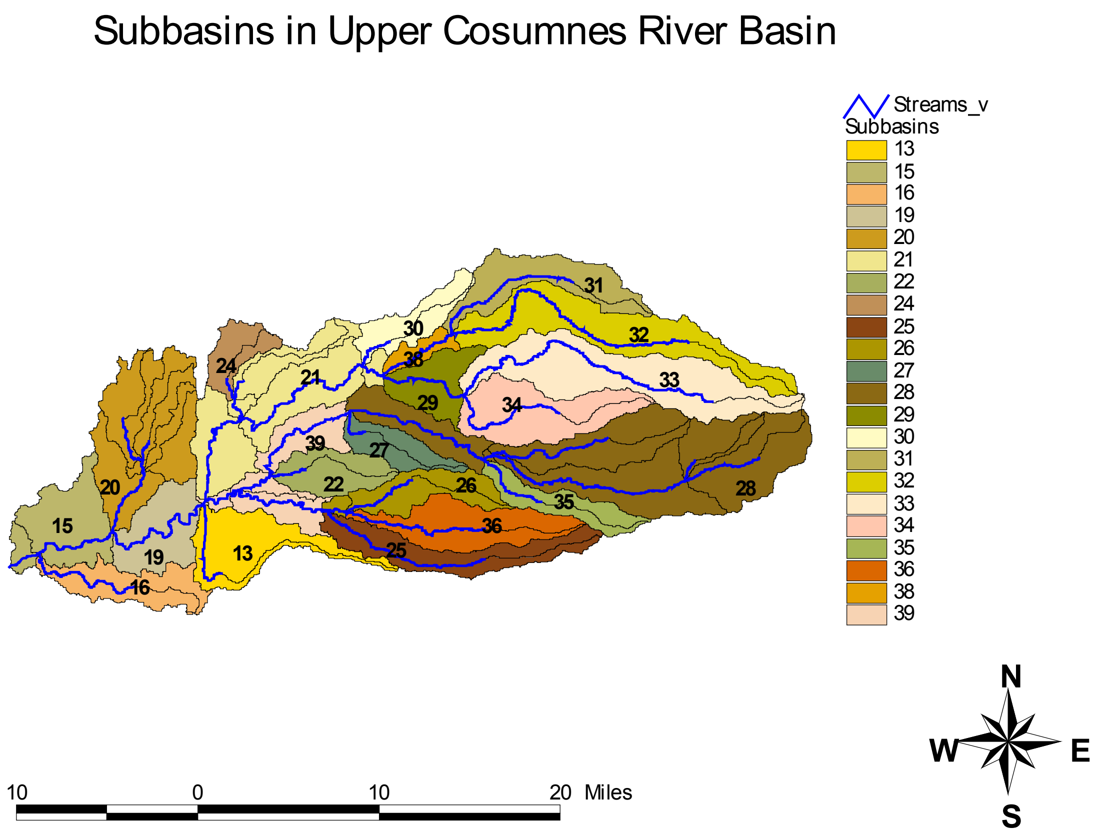


Figure 21. Subbasins and Hydrologic Response Units (HRUs) for the HMCRB. Each polygon represents one HRU and one subbasin may contain one or more HRUs.

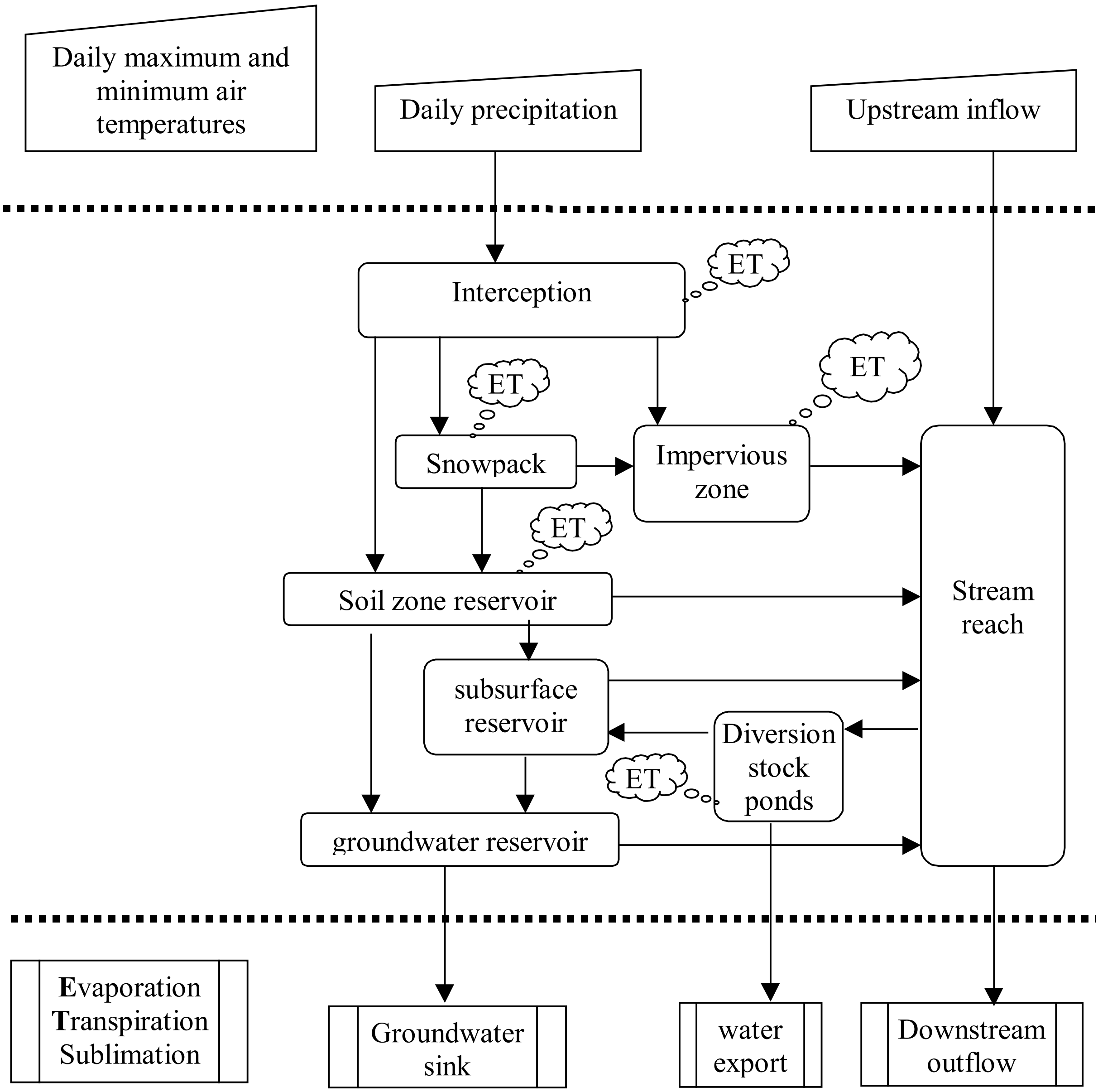


Figure 22. A diagram showing all input, output and storage terms accounted for by the MMS-HMCRB. The top part shows the inputs, the middle part shows the storage terms, and the lower part shows the outflows.

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6.2 Model Calibration

Since MMS-HMCRB is a conceptual lumped hydrologic model, most of the model parameters need to be determined by calibration. Calibration is a process of varying the coefficients (parameters) of the model in order to make the simulated daily flow hydrographs match the observed hydrographs in the basin. Calibration and evaluation of MMS-HMCRB were done as follows.

1) selecting stream gage stations in the basin and delineating the basin into HRUs and subbasins;
2) selecting hydrometeorological observation stations in the basin and associating each HRU to a hydrometeorological observation station;
3) determining the default model parameters using available information such as DEM, soil data and vegetation data.
4) identifying hydrologic processes that have significant effects on the stream flow and identifying the parameters of the hydrologic processes that have most influence on the stream flow;
5) adjusting the identified model parameters and making the simulated daily flow hydrographs match the observed hydrographs as closely as possible;
6) verifying the model by simulating water conditions in a selected historical time period during which observed precipitation data, observed air temperature data and observed stream flow data were available in the basin.

The actual calibration procedure for a particular hydrologic basin depends on what types of observation data are available in the basin. MMS-HMCRB has been calibrated by historical climatic data (daily precipitation and daily maximum and minimum temperatures), historical stream flow data and the diversion data. Historical stream flow data from six stream gage stations in the Cosumnes River basin and historical climate data at nine climate observation stations around the Cosumnes River basin, as shown in Figure 23, are available for various time periods within the last 90 years. The McConnel stream gage station is located in the lowest part of the Cosumnes River basin. Upstream of the McConnel stream gage, the Cosumnes River basin was delineated into 39 subbasins, which were further divided into 83 HRUs for the model (see annual report of project year 1998-1999).

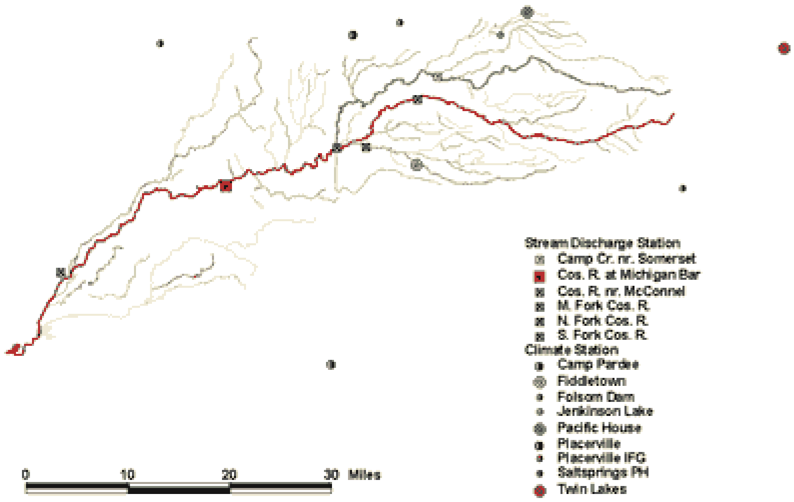

Figure 23. The stream discharge and climate observation stations in Cosumnes River region.

The historical stream discharge data at the gage station of North Fork Cosumnes River near El Dorado and at the gage of South Fork Cosumnes River near River Pines were used in the parameter calibration for the HRUs at the upstream of the corresponding gage stations, respectively. The model parameters of the HRUs from which water flows into the stream reach between Michigan Bar and McConnel gage stations were calibrated based on historical discharge data at McConnel gage station obtained before 1982. The McConnel stream gage station does not have stream discharge records after 1982. The other two stream gage stations that are currently operational in Cosumnes River basin are Camp Creek near Somerset and Michigan Bar gage stations. Both of them have stream discharge records available. The Michigan Bar gage station has the most complete stream discharge record in the basin. Since no discharge data are available at McConnel after 1982, the evaluation of the model performance can not be done for subbasins between Michigan Bar and McConnel gage stations under the basin conditions after 1982. The model evaluation in this report was based on observed stream discharges at Michigan Bar and was done for the subbasins that are located upstream of Michigan Bar gage station, as shown in Figure 22. The Michigan Bar stream gage is located at the outlet of subbasin #15.

Diversion data need to be incorporated into the model as fixed model parameters before calibration. The diversion data was developed from the water rights permit data in the State Water Resources Control Board (SWRCB) of California and topographic maps. In order to quantify the flow process caused by diversions, MMS-HMCRB uses the following information: diversion limit, diversion's source HRU, area of a diversion pond, volume of a diversion pond, diversion pond's HRU, diversion's on-day in a year, diversion's off-day in a year, and the date when the water right was granted for a diversion. Figure 24 shows the spatial distribution of diversion limits in Cosumnes River basin upstream of Michigan Bar.
The hydrometeorological stations that have daily precipitation and air temperature observations inside the basin and/or near the basin boundary were then assigned to each HRU of the model. This assignment determines how much precipitation each HRU will receive and what maximum and minimum daily air temperature the HRU will have. The most important parameters in the MMS-HMCRB that control the water balance of the model are the precipitation adjusting factors and the coefficients of the evapotranspiration

process. The precipitation adjusting factors represent the differences between the observed precipitation amount and the received precipitation amount by each HRU in the model. These parameters are the controlling parameters for the water balance in the model. The parameters for snowmelt processes in the upper basin have effects on the stream flow not only in the winter snow season, but also in the spring and summer because there may exist snow cover in the upper Cosumnes River basin even in June of the year. The coefficients of the nonlinear subsurface reservoirs and the linear groundwater reservoirs have significant impacts on the recession part of the hydrograph that is simulated by the model.

Some of the parameters in MMS-HMCRB can be estimated roughly using the digital elevation data, soil type map, land use and land cover maps, and vegetation map, which contain the basic geographic and physical information of the basin. Using the soil and forest data in STATSGO data set of California, we have generated a data set that describes the physical properties of the land surface in Cosumnes River basin. This data set includes the spatial distributions of the soil depth from surface to bedrock or impermeable soil layer, soil porosity, soil hydraulic conductivity, standard deviation of the log of soil hydraulic conductivity, and forest cover. Some of the data in this data set may not be useful for MMS-HMCRB, such as the soil hydraulic conductivity and its standard deviation, but they can be used with a physically-based watershed model under development for the upper Cosumnes River basin.

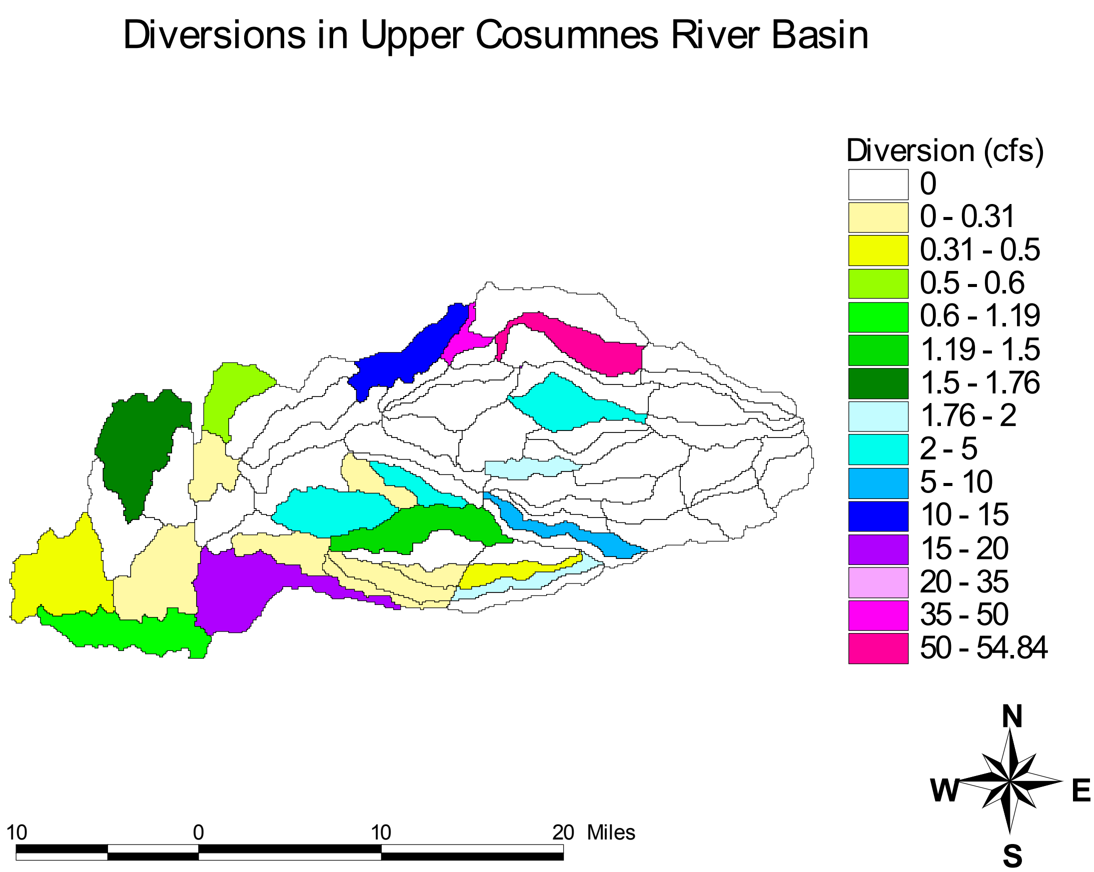

Figure 24. Spatial distribution of diversion limits in Upper Cosumnes River Basin. The values in the figure represent the sum of diversion limits in a HRU.

The graphical user interface of MMS-HMCRB makes the task of adjusting the parameters in the model very easy, but we need to know what to adjust since there are thousands of parameters in the model which can be adjusted.

6.3 Effects of Spatial Precipitation Distribution

Preliminary calibration results have shown that further improvements in the precipitation and temperature inputs to the HMCRB are required. Successful simulations for both flood peak flow and fall low flow depends on the precipitation and temperature distributions. The two simulation cases, as shown in Figure 25, used the same parameter set, except the precipitation station assignments to HRUs of the model are different. The peak flood discharge simulated using the original assignment was only half of the observed discharge at Michigan Bar for the 1986 flood. On the other hand, the HMCRB produced an almost perfect prediction of the flood discharge with the new precipitation station assignment. The results from these simulations are plotted in Figure 26.

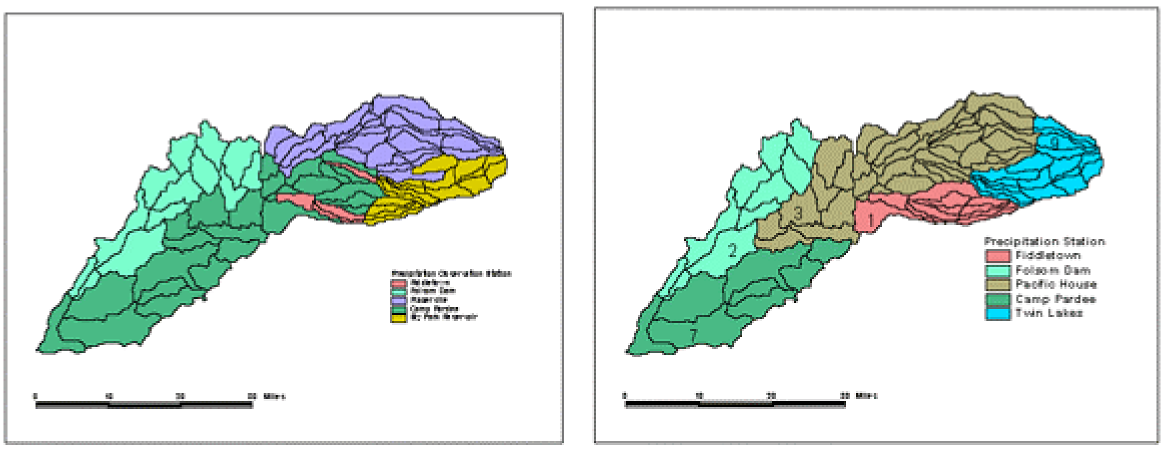

Figure 25. Two different precipitation station assignments. The left is the original assignment. The right is the new assignment.

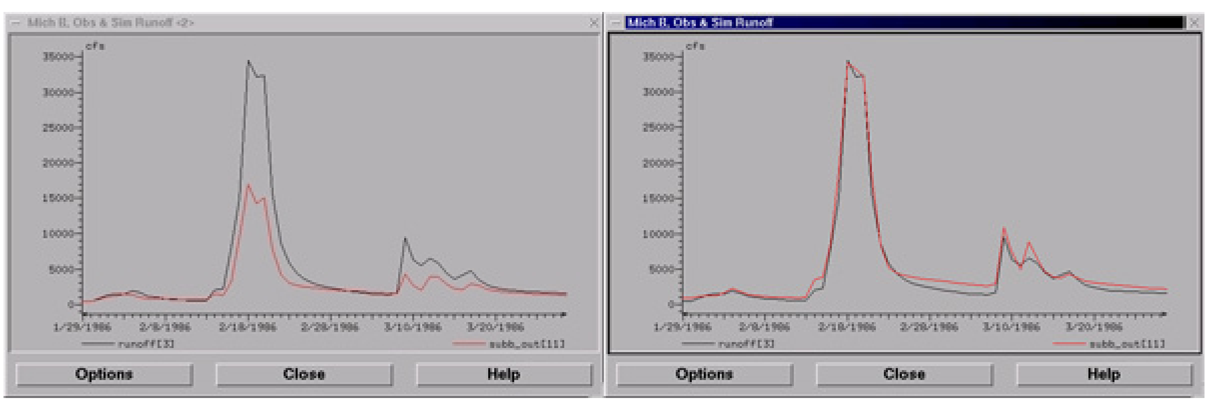

Figure 26. Comparison of hydrographs simulated using different precipitation station assignments. Black lines show the discharges observed at stream discharge station #3 (Michigan Bar) . Red line on the left plot shows discharges simulated with the original precipitation assignments and red line on the right plot shows

the simulated with the new precipitation assignments. The simulated flow discharge above is the discharge at the outlet of subbasin #11 where Michigan Bar is located.

6.4 Simulation Results and Discussions

In order to examine the performance of MMS-HWCRB with the calibrated parameter set, we have simulated stream discharges at Michigan Bar from 1984 to 1997 under two scenarios, i.e. with diversion and without diversion. The full-scale hydrographs in Figure 26, which were generated by the simulation, show the daily mean discharges in the range of 0 to 60,000 cfs between 1984 to 1997. The 3 plots in Figure 27 show the hydrographs between 1984 to 1989, hydrographs between 1989 to 1994, and hydrographs between 1994 to 1997, respectively. The two big flood events of 1986 and 1997 are clearly shown in Figure 27. The long lasting drought between 1987 to 1992 is also shown clearly in both Figure 27 and Figure 28.

In order to identify the low flow conditions, only the discharges in the range of 0 to 200 cfs were plotted in Figure 28. The observed discharges in the figure indicate that the Cosumnes River dried out (zero-cfs-flow at Michigan Bar) during summer and/or fall in the seven drought years. It can be seen in Figure 28 that the model did not make a reasonable prediction of low flow conditions when comparing the observed discharges with the simulated discharges in low flow periods. For example, the observed discharges show that Cosumnes River dried out only in 27 drought years, but the model predicts that Cosumnes River has dried out in summer or fall almost every year during the 14-year period, as shown in Figure 28.

The discharges simulated with diversion and the discharges simulated without diversion are almost identical in the low flow periods, as shown in Figure 28. This shows that diversions do not have significant impact on the model prediction of the fall low flow in upper Cosumnes River basin. From the results obtained under the two scenarios, we may conclude that legal diversions in the upper Cosumnes River do not have obvious effects on low flow conditions in Michigan Bar. Such a conclusion is questionable. There is either no water in the stream for diversion, or the diversion is not allowed in low flow periods. The diversion data shows that most of the diversions are allowed in winter or spring but not in summer or early fall. By removing the few big water diversions in upper Cosumnes River, which were shown as red and purple coverages near the Jenkinson Lake and the South Fork of Cosumnes River in Figure 24, the total diversion amounts in upper Cosumnes River can be reduced significantly and the rest of the diversions in the upper Cosumnes may only have minimal impact on the low flow conditions at Michigan Bar.

The diversion model in MMS-HMCRB assumes that people will divert the maximum amount of water that is legally allowed because we do not have the actual diversion data available. The model mistakenly predicts dried-out conditions at Michigan Bar in wet years such as 1995 and 1996 because of the above assumption, as shown in Figure 28. This unrealistic assumption makes model calibration very difficult. The explicit diversion model with unrealistic diversion data does not produce good predictions. Water may be released from Jenkinson Lake in the summer or fall, but there is no reservoir operation module in MMS-HMCRB. A more realistic approach should incorporate the water demands by crop and vegetation into the model. More field investigations are needed in order to identify the consumptive use and evapotranspiration patterns in the basin.

The fall low flows in Cosumnes River are affected by the soil moisture storage accumulated in winter and spring in the basin and by the evapotranspiration during spring and summer. The timing of the snowmelt at the upper basin has a significant effect on floods and fall low flows. Accurate distributions of precipitation and temperature in the basin are two of the determining factors for the success of the flood flow and fall low flow simulations. Good temperature measurements are currently available at only two of the nine climate stations shown in Figure 23. Spatial distribution of air temperatures determines the spatial distribution of precipitation type in the model. It also controls the snowmelt process in the model. Just two temperature observation stations can not provide sufficient information to quantify the spatial distribution of air temperature in the basin. Simulation results have shown that further improvement in precipitation and temperature inputs to MMS-HMCRB are required. Successful simulations for both flood peak flow and fall low flow depends on the precipitation and temperature distributions. Therefore, we may need to add more hydrometeorological observation stations into the basin, or to utilize numerical meteorological models to provide the model with more consistent hydrometeorological input data.

Relating geological, physical, and biological characteristics of the Cosumnes River basin to the parameters of a hydrologic model is essential for assessing the hydrological impacts of land use and water management scenarios in a basin like Cosumnes River basin. It is very difficult to do such an incoporation with MMS-HWCRB since the most important parameters of the model were determined by calibration. On the other hand, it will be much easier to simulate the hydrologic conditions under different management scenarios using physically based watershed hydrologic models because their model parameters can be related directly to physical, geological, and biological attributes of a watershed. Therefore, a physically based watershed hydrologic model for Cosumnes River basin is more appropriate as a tool for predicting what will happen with different management scenarios.

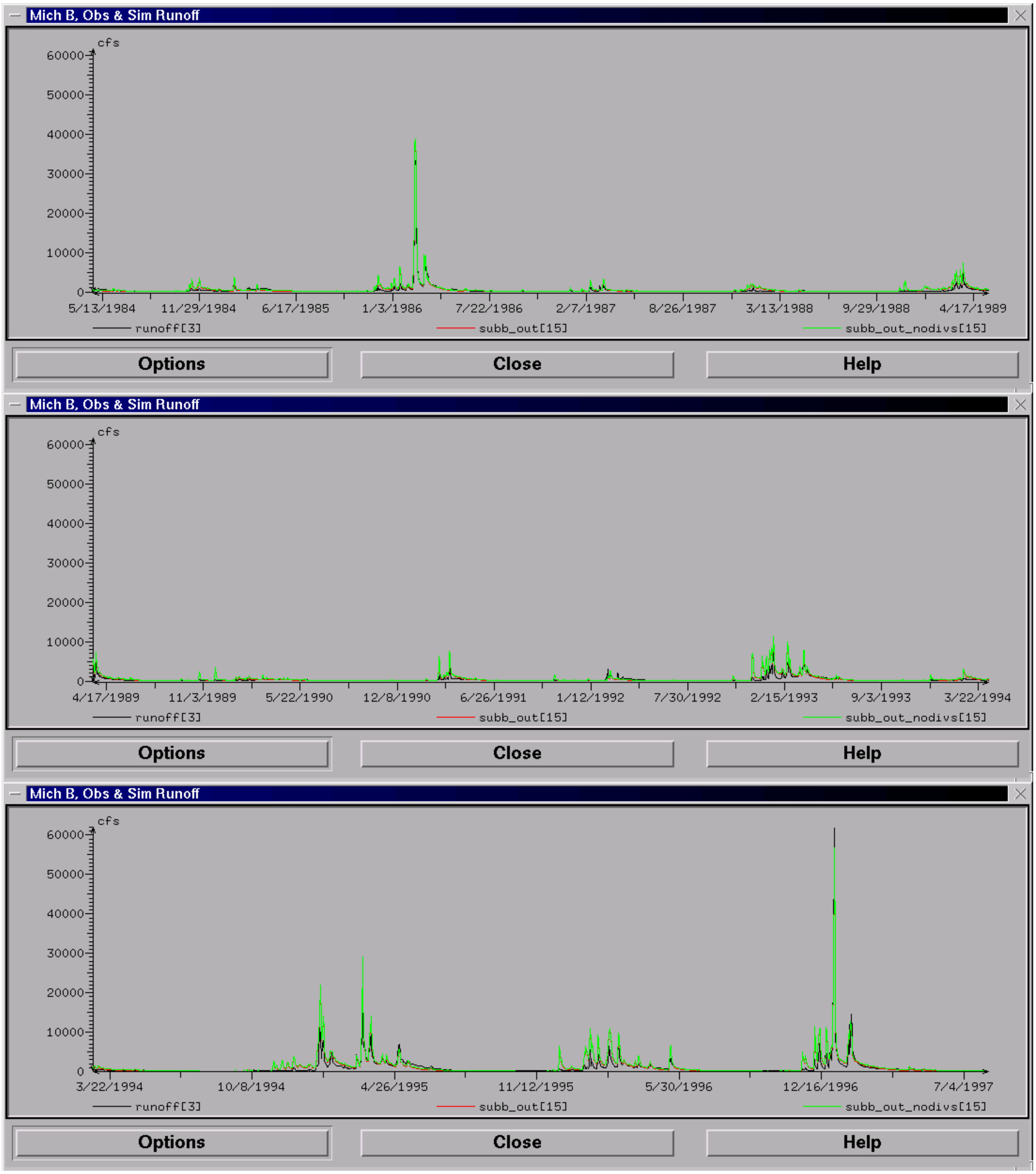

Figure 27. Comparison of observed stream flow (black line), simulated stream flow with diversion (red line), and simulated stream flow without diversion (green line) at Michigan Bar from 1984-1997.

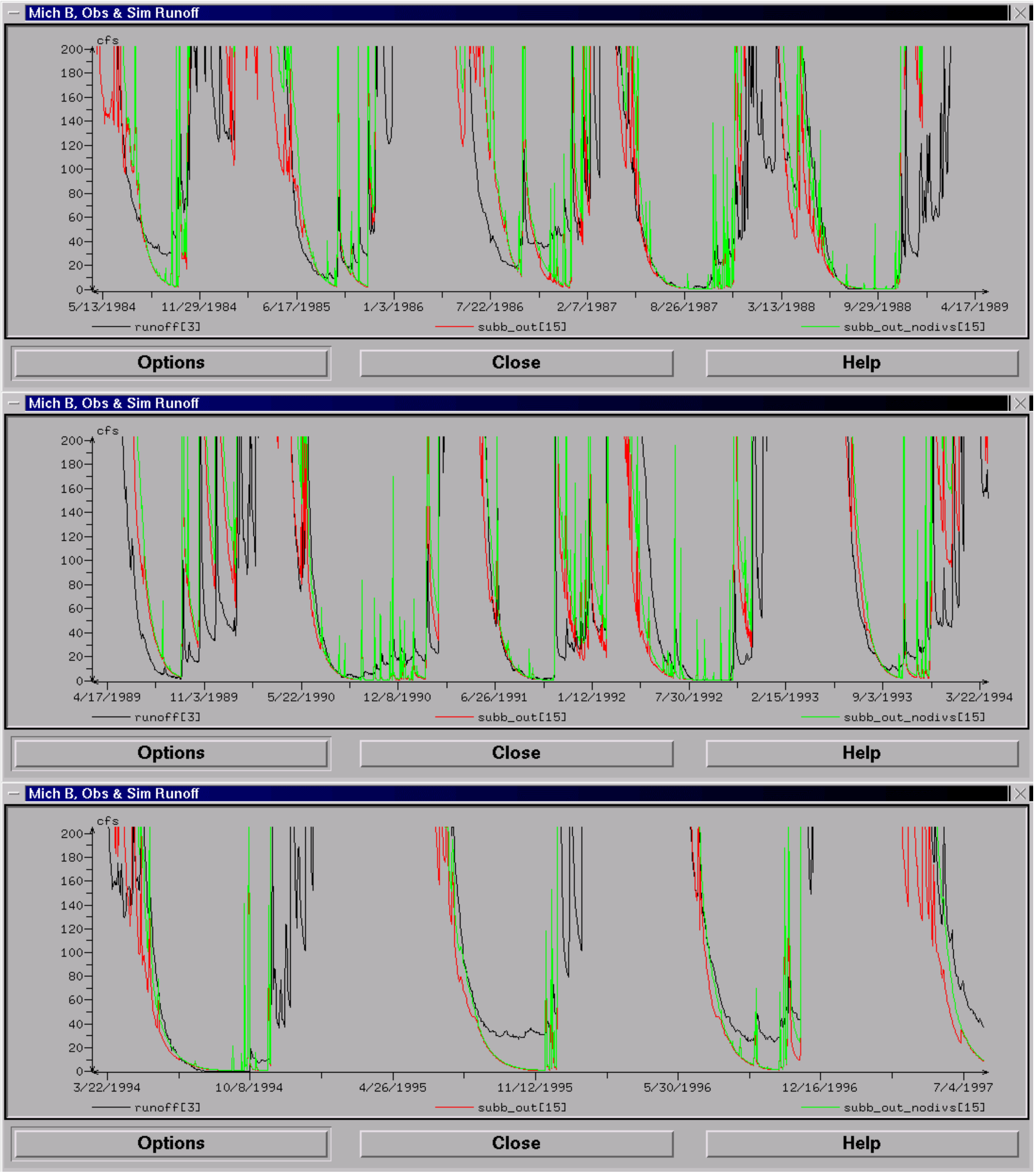

Figure 28. Comparison of observed stream flow (black line), simulated stream flow with diversion (red line), and simulated stream flow without diversion (green line) at Michigan Bar from 1984-1997 in the low flow range of 0-200 cfs.

7. Field investigations

Field measurements to characterize local scale interactions between shallow groundwater and the river were continued throughout the last year of the project. Measurements included stream gauging, seepage meter measurements, shallow groundwater monitoring and measurements of vertical temperature profiles below the stream channel according to a methodology outlined in Constantz and Thomas (1996). Obtained data generally supported conclusions drawn from the numerical simulations and from previous field work. The river in the lower basin is mostly in effluent conditions. Seepage rates in summer 1999 ranged from upward flow of 0.88 x 10^{-6} m/s to downward flow of 0.32 x 10^{-6} m/s (Figure 29). Seepage rates in summer 2000 ranged from upward flow of 0.86 x 10^{-6} m/s to downward flow of 0.63 x 10^{-6} m/s (Figure 30). In both years measurements occasionally showed influent conditions at Wilton Road. Stream bed material at this site consists of a coarse sand and it is suspected that lateral hyporeic inflow through the coarse bed material into the seepage meter may have caused the influent readings. Influent conditions at Dillard Road in the late summer of 2000 occurred after an unusual summer rainfall event. Temporarily perched aquifers on low permeability layers above the regional water table may have formed from infiltrating rain and could have caused inflows into the river channel.

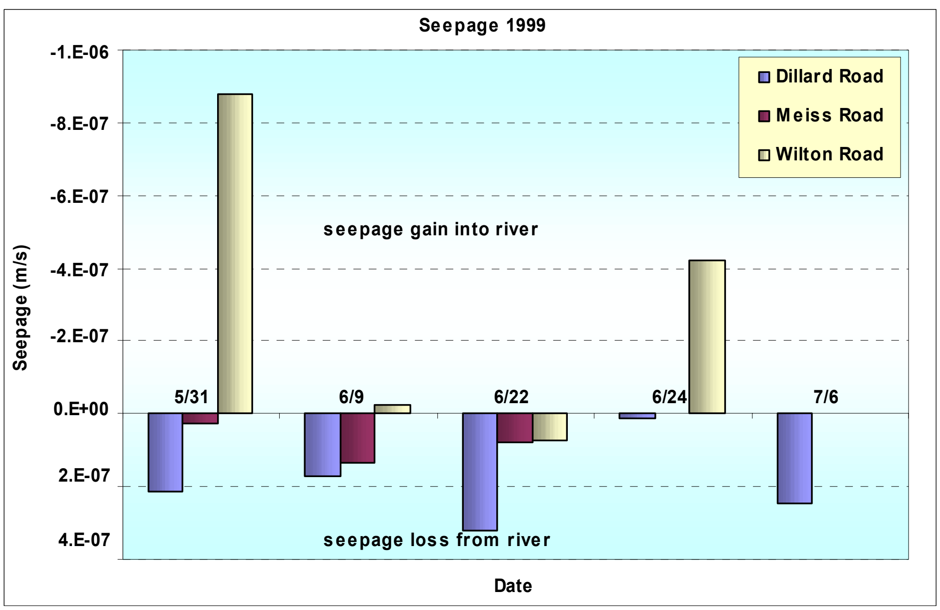

Figure 29. *Seepage meter measurements summer 1999.*

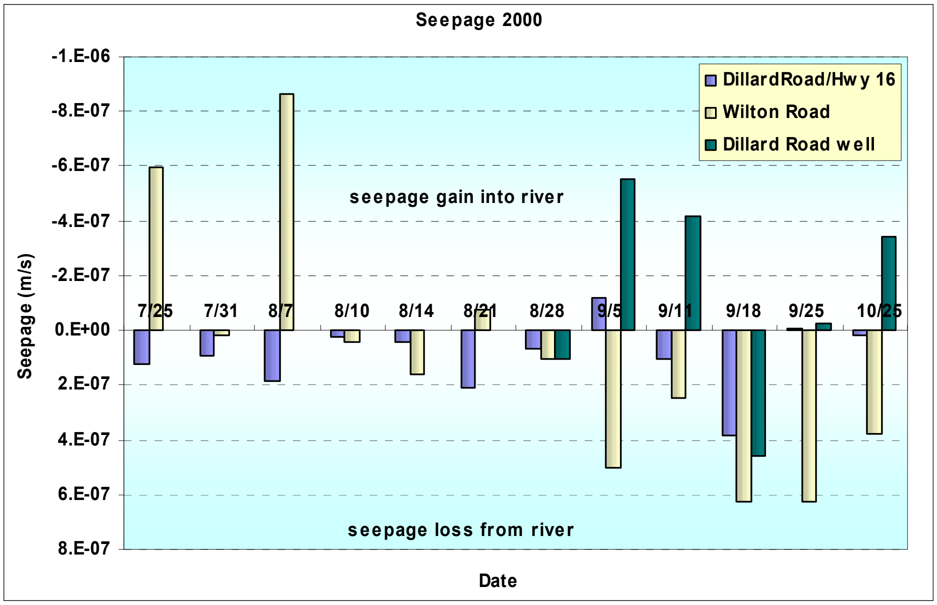

Figure 30. *Seepage meter measurements summer 2000.*

Streamflow measurements also suggest losing conditions in the river during most of the summer and early fall (Figures 31 and 32). Streamflow was measured with a propeller type current meter using the area velocity method at the following locations along the lower Cosumnes River: MHB (stream flow taken form USGS gauge / river mile 36.1), Highway 16 (river mile 32.7), Dillard Road (river mile 27.5), Meiss Road (river mile 24.8), Wilton Road (river mile 17.3)and Highway 99 / MCC (before confluence with Deer Creek / river mile 11.3). Streamflow losses were calculated as the difference between upstream and downstream flow. Losses calculated that way not only include seepage losses but also losses due to diversions and evapotranspiration. Various smaller diversions exist along the lower Cosumnes, but many of them are evidently not operated. Quantitative data on surface water diversions in the lower Cosumnes were not available. The water district bordering most of the lower river (Omochumne Hartnell Water District) does not divert surface water from the river (Ron Lowry, Omochumne-Hartnell Water District, personal communications 2001). A larger diversion at Rancho Murieta only diverts flows during the wet season. Based on this information and observations in the field, we believe that impacts of diversions on our summer and early fall streamflow measurements are small.

Riverflows steadily decrease with downstream distance throughout the summer. Later in the year this pattern partly reverses, and flows increase between MHB and Dillard Road. In 1999 this pattern was observed in December when the first rainfalls of the wet season had occurred already and smaller tributaries, which had been dry throughout the summer, started flowing again. In 2000, however, the same reversal occurred much earlier in the year (September), before the first fall rains. That could indicate that the river reaches upstream of Dillard Road had switched from losing conditions to gaining conditions, probably in response to rising water tables and initiated baseflow after the end of summer irrigation, supporting the hypothesis stated earlier that the reaches upstream of Dillard Road seasonally receive baseflow. Other reasons for this gain in flow could have been baseflow from perched water tables that have built up from continuous irrigation over the summer or contributions from irrigation return flows. Available data was insufficient to clearly single out one major source responsible for these observed gains in flow.

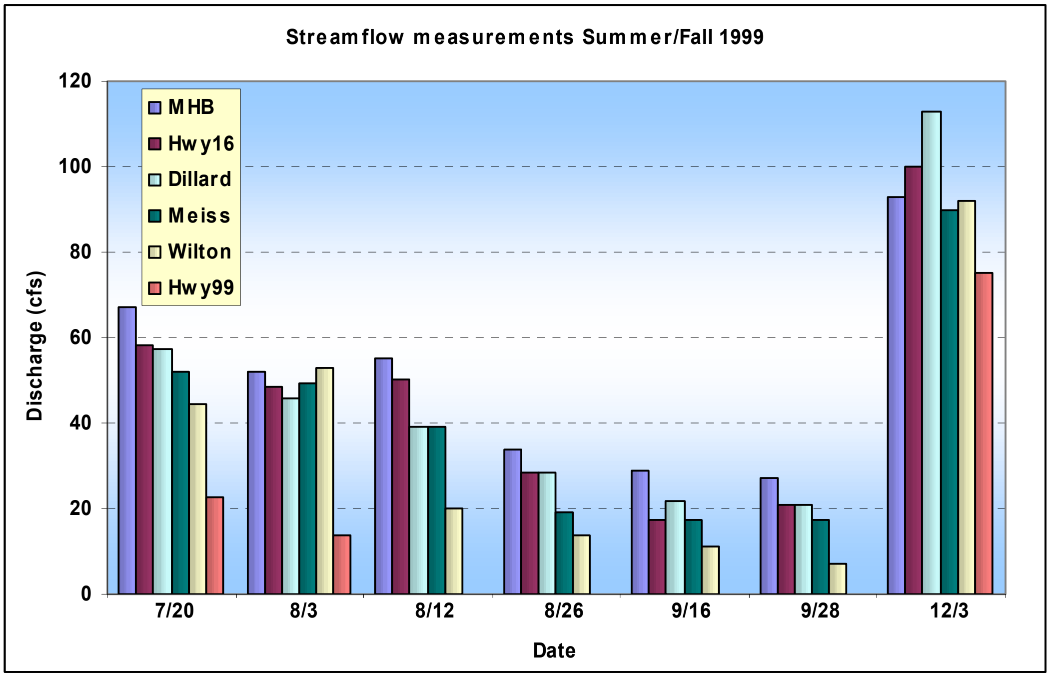

Figure 31. *Streamflow measurements summer 1999.*

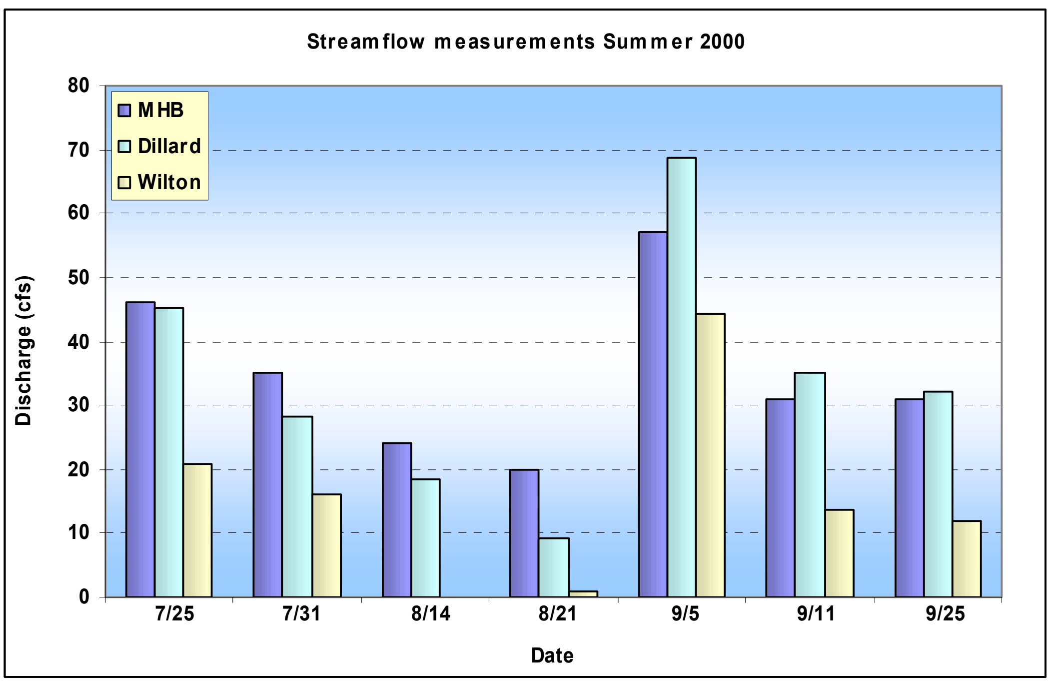

Figure 32. *Streamflow measurements summer 2000.*

The same pattern can be seen in figures 33 and 34, which show flow losses per river-mile for 1999 and 2000. Both reaches are losing flow throughout the summer but the upstream reach (MHB to Dillard Raod) starts gaining later in the season. Streamflow losses in summer 1999 ranged from a gain of 2.3cfs per river-mile to

a loss of 2.1cfs per river-mile (Figure 33). Similarly, streamflow differences in summer 2000 ranged from a gain of 2.5cfs per river-river mile to a loss of 1.5cfs per river-mile (Figure 34).
As would be expected river-flow losses calculated from stream gauging tend to be greater than those obtained from extrapolating seepage rates from seepage meter point measurements to the reach scale. Average losses per river-mile obtained from seepage meter measurements were approximately 0.008 to 0.75cfs/river-mile, whereas river-flow losses calculated from stream gauging measurements ranged from 1.02 to 1.77cfs/river-mile. Differences arise from the fact that gauged flow losses include losses due to evapotranspiration and diversions not accounted for by seepage meter measurements. Also seepage meter measurements represent single point measurements of seepage rates and error is introduced by extrapolating these measurements to the reach scale. Furthermore, random point measurements of seepage tend to preferentially sample the low hydraulic conductivity values, because hydraulic conductivity in naturally heterogeneous materials tends to be distributed log-normal.

Temperature gradient measurements across the river channel and river bed material were conducted at three sites. Thermisters were place at the river bed and at 3, 6 and 9 ft below the river bed. Pronounced diurnal variations were observed in the river water but not in groundwater temperatures (Figure 35), indicating a loose coupling between surface water and shallow subsurface water. The groundwater temperatures are generally relatively steady and cool. If the river would receive substantial baseflows, water diurnal surface water variations would probably be less pronounced. At Dillard Road and Highway 99 only the shallowest thermister showed a clear response to changes in river water temperature, whereas at Wilton Road a response can be seen in the thermisters at all three depths. That suggests a larger mixing zone (hyporeic zone) between surface and shallow subsurface water at Wilton Road than at the other two sites, probably due to the coarser river bed material at this site.

A recently completed monitoring piezometer in the river channel at Highway 99 confirms the hydraulic disconnection between the river and aquifer at that location in mid-summer, 2001. The water table was found to be approximately 30 ft below the channel. Observed outcrops of cemented hardpans and clay beds in the river channel as well as evidence of perched water tables above the regional water table point at geologic heterogeneity as an important local controlling factor for river aquifer exchange. A better characterization of these heterogeneities could help to improve quantification of this exchange and may provide additional opportunities for river flow restoration.

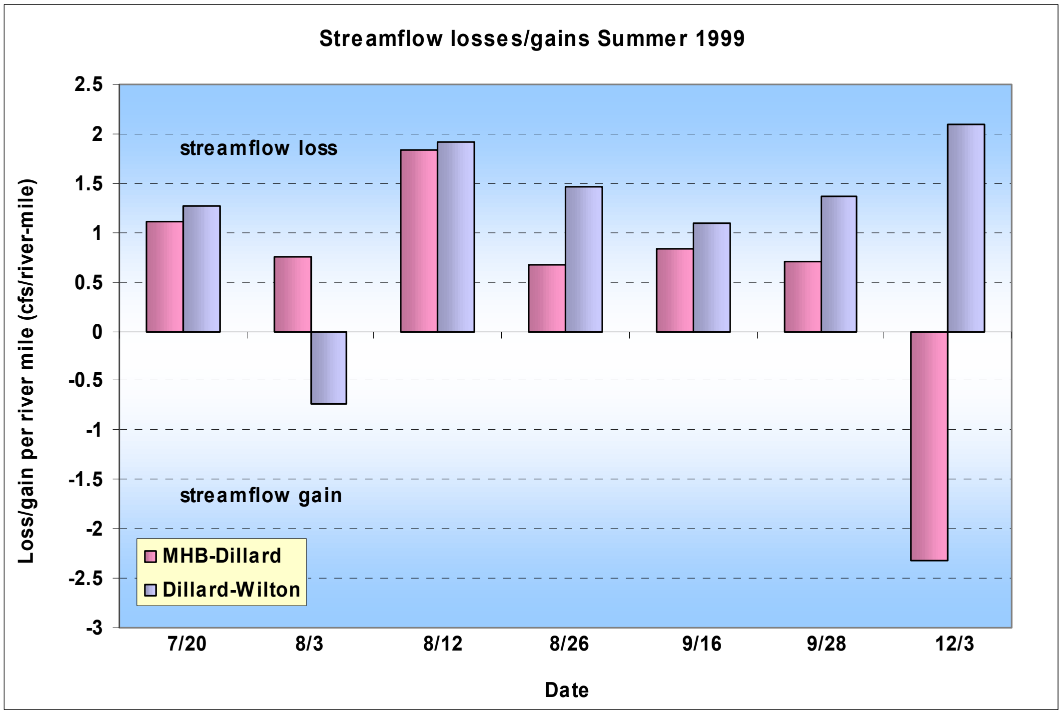

Figure 33. *Streamflow loss/gain per river miles summer 1999.*

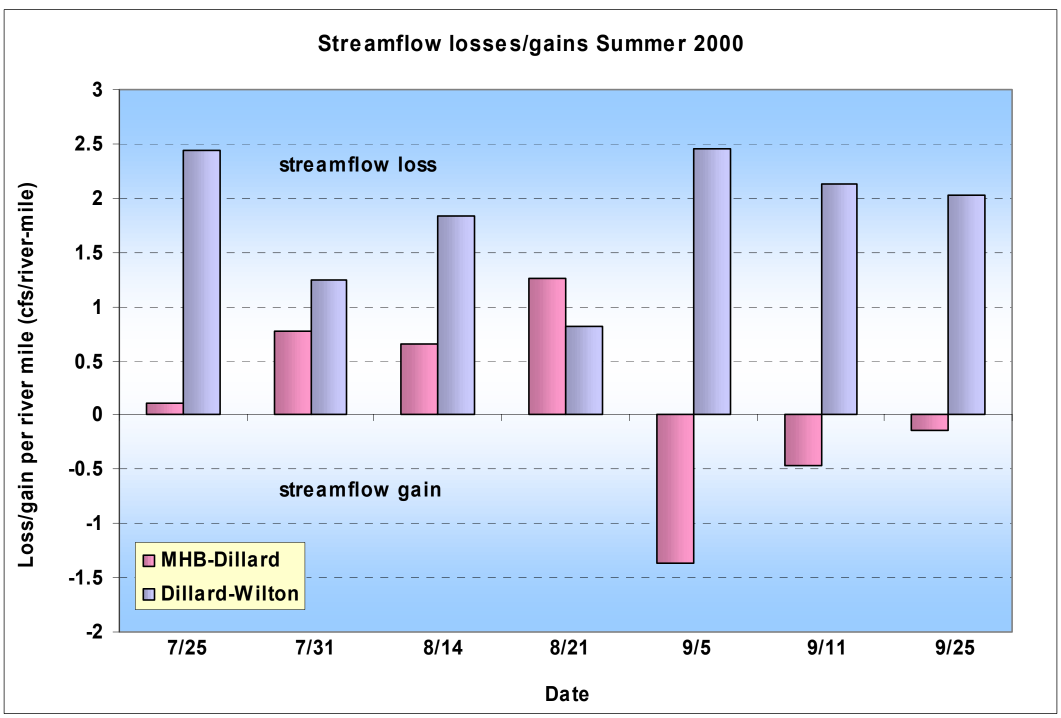

Figure 34. *Streamflow loss/gain per river mile summer 2000.*

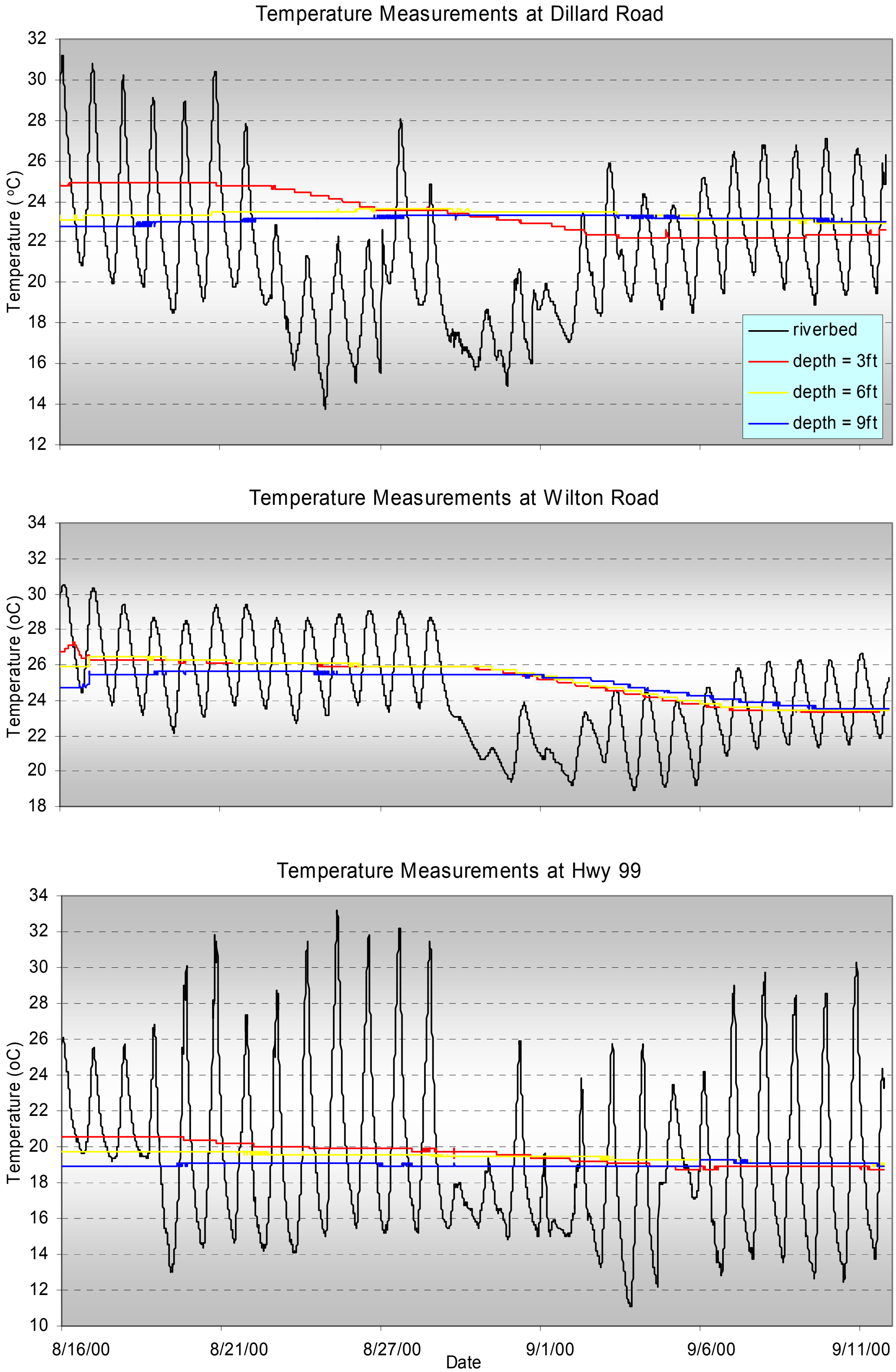

Figure 35. *Temperature measurements.*

8. Conclusions

Investigations of local and regional scale groundwater surface water interactions along the lower Cosumnes River (river miles 0-36) have confirmed that most, but not all, of the river channel is hydraulically disconnected from the regional aquifer. That means that groundwater levels lie below the elevation of the channel bottom for extended reaches of the river; and in those reaches the river losses water due to downward seepage. Where the river is disconnected from the regional aquifer, additional declines in groundwater levels do not affect the rate of downward seepage. The disconnection is most pronounced in the middle reaches between Highway 99 and Meiss Road (river miles 11 to 25.8) where groundwater levels seasonally fluctuate between 30 and 50 ft below the river channel. Upstream of Dillard Road (river mile 27.5) groundwater levels come closer to the surface and rise to within a few feet below the river channel at the end of the wet season. Similar conditions prevail in the lower reaches of the river, around Twin Cities Road (river mile 5), where groundwater levels fluctuate between 3 and 15 feet below the channel. Downstream of Twin Cities Road the water table comes even closer to the surface, within approximately 10-12 ft in the summer and fall.

In these areas upstream of Dillard Road and downstream of Twin Cities Road, the river receives baseflow at least seasonally. The river reaches around Twin Cities Road and upstream of Dillard Road constitute sensitive transition areas in which hydraulic connection between the river and the aquifer may temporarily be established. Significant lowering of groundwater levels in these areas could further diminish river flows. River flows over the extended middle reaches of the lower Cosumnes between Meiss Road and Highway 99 are unaffected by groundwater level fluctuations under current conditions. These reaches receive no baseflow contributions and the river is predominantly effluent or losing here. Flow losses from seepage and evapotranspiration based on stream flow measurements ranged from 1.02 to 1.77cfs/river-mile. Point seepage measurements of river seepage showed a large variability of seepage rates. Losses ranged from –0.86 to 1.31 µm/s Occasionally seepage meters recorded influent conditions, either indicating lateral hyporeic inflows into the seepage meter through coarse riverbed material or flow contributions from locally perched aquifers above the regional water table. Local geologic heterogeneity appears to be an important factor in controlling river aquifer exchange. Further research is needed to quantify these effects.

The hydraulic disconnection along the lower river is reflected in the calibration and baseline simulations with the regional groundwater model. However, whereas groundwater levels in the upper and middle reaches are represented fairly well, the model tends to significantly underestimate groundwater levels in the lowest reaches. Contrary to the groundwater monitoring data, the model suggests a complete hydraulic disconnection in the lowest reaches of the river (downstream of Twin Cities Road).

Under baseline conditions annual seepage losses from the Cosumnes channel between MHB and MCC range from 40,000 ac-ft in dry years to 90,000 ac-ft in wet years. These values are comparable to values obtained from stream flow records between 1965 and 1969 in a study by DWR, which quotes annual seepage losses between 30,000 and 130,000 ac-ft for the same river reach (DWR, 1974). Mean monthly river flows simulated by the model show that for moderate fall inflows from Michigan Bar (< 100cfs), most river flow is lost between MHB and MCC. Similar behavior has been observed in stream flow measurements in late summer and early fall (Figure 30).

A zero-pumping scenario as well as analysis of historical data suggest that the Cosumnes river has probably been in hydraulic contact with the aquifer and received baseflow along its entire length before major groundwater development occurred in the county in the 1950s and 60s. Interestingly, however, simulations show that even under zero pumping the upper most reach between MHB and Dillard Road experiences annual net losses, indicating that the Coumnes River even under "natural" conditions may have alternated between gaining and losing in some reaches.

Folsom South Canal (FSC), crossing the river at river mile 23, provides a potential water source for flow augmentation as an immediate measure to enhance fall flows. Discharge of 50 cfs from FSC to the Cosumnes channel from September to December, as simulated in scenario 1, would significantly improve fall flows downstream of FSC, although in average 60% of the augmented flow is lost to additional seepage. Reducing seepage losses by reconnecting the regional aquifer with the river channel would require large amounts of water. Annual reductions in pumping of 166,000 ac-ft were necessary to partly reconnect the river in the upper reaches. Reductions on the order of 250,000 ac-ft, almost 50% of the annual baseline groundwater pumping, were required to achieve that goal in the lower reaches. Resulting annual decreases in seepage losses ranged from 10,000 to 20,000 ac-ft in the upper and lower river reaches. Simulated potential increases in fall flows simulated by the model, however, were fairly small, indicating an unfavorable cost-effect ratio. The model further suggests that combining upstream pumping reductions with flow augmentations from FSC could achieve the largest improvements in fall flows because less of the augmented water is lost to seepage due to the partially reestablished hydraulic contact between river and aquifer in the upper reaches. The additional seepage losses due to flow augmentation provide the additional benefit of recharging groundwater.

The simulations show that enormous amounts of water would be needed to even just locally recover groundwater levels and restore baseflows to the Cosumnes River. Larger improvements of fall flows with less amounts of water can be achieved with flow augmentation, suggesting such measures as the most viable short and intermediate term solutions. Efforts like the restoration of a natural flood regime along the lower Cosumnes, under which larger areas of the floodplain are regularly inundated, appear to provide significant recharge and should be encouraged. Results of this study point toward a three-part strategy for improving stream baseflows and sustaining regional groundwater resources: augmentation of surface flows, management of groundwater pumping, and restoration of natural flood regimes. Understanding the combined effects of all these measures over the long term (multi-decades) is key to management of the Cosumnes basin. Given the foundation laid by the present study, follow-up analyses capable of addressing such complex issues would be the next logical step. Such analyses will require better understanding of local and regional scale hydrostratigraphy as well as more reliable numerical models of interplay between the stream, vadose zone, and aquifer system.

The results presented in this final report along with other documentation and information related to this project will be posted on a web page in the near future.

Acknowledgements: We would like to thank the US Fish and Wildlife Service for their financial support of this study and the Nature Conservancy and the Center for Integrated Watershed Sciences and Management at UC Davis for their invaluable cooperation and support. Our thanks also go to Jonathan Goetz, for providing the up-dated Sacramento County model, and DWR for their help in establishing our groundwater monitoring network.

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10. Appendices

I - UC Davis monitoring network and groundwater levels in selected wells in the vicinity of the river
II - Calibration results for selected wells in the lower Cosumnes Basin
III - Map of 1997 flood extend and additional recharge areas in the groundwater model

To monitor groundwater table elevations with respect to channel elevation in the vicinity of the river a network of 33 monitoring wells was established. The network consists of existing agricultural irrigation and domestic wells and is based on an existing network run by the Department of Water Resources. Additional wells in the vicinity of the river, which were easily accessible and for which monitoring permission could be obtained, were added to the network. Figure 1 shows a map of the UC-Davis monitoring network.

Groundwater levels were monitored every two weeks between April 2000 and October 2001. When individual wells were pumping or were not accessible at the time of monitoring no reading was taken. Seasonal groundwater level fluctuations ranged from 3.5 to 20.1 feet and averaged 10 feet. Agricultural wells usually showed larger seasonal fluctuations due to a pronounced distinction between pumping and no-pumping seasons. Groundwater levels in wells in the immediate vicinity of the river reflect the hydraulic disconnection between the regional aquifer and the river. In the lowest river reaches around Twin Cities Road and in the uppermost reaches around Dillard Road groundwater levels came within a few feet of the river channel elevation towards the end of the wet season. The following figures show locations of individual wells and their groundwater levels over the monitoring period.

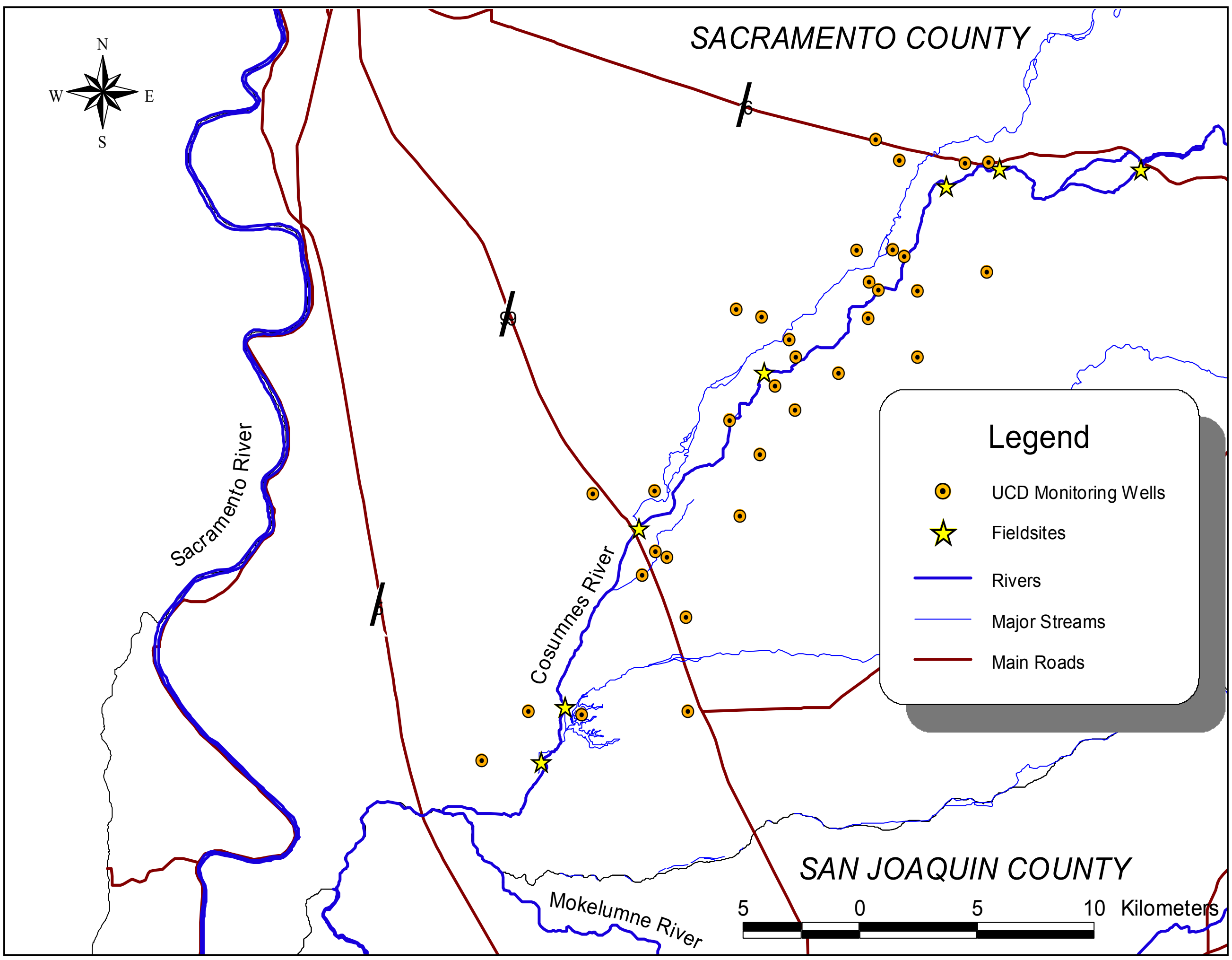
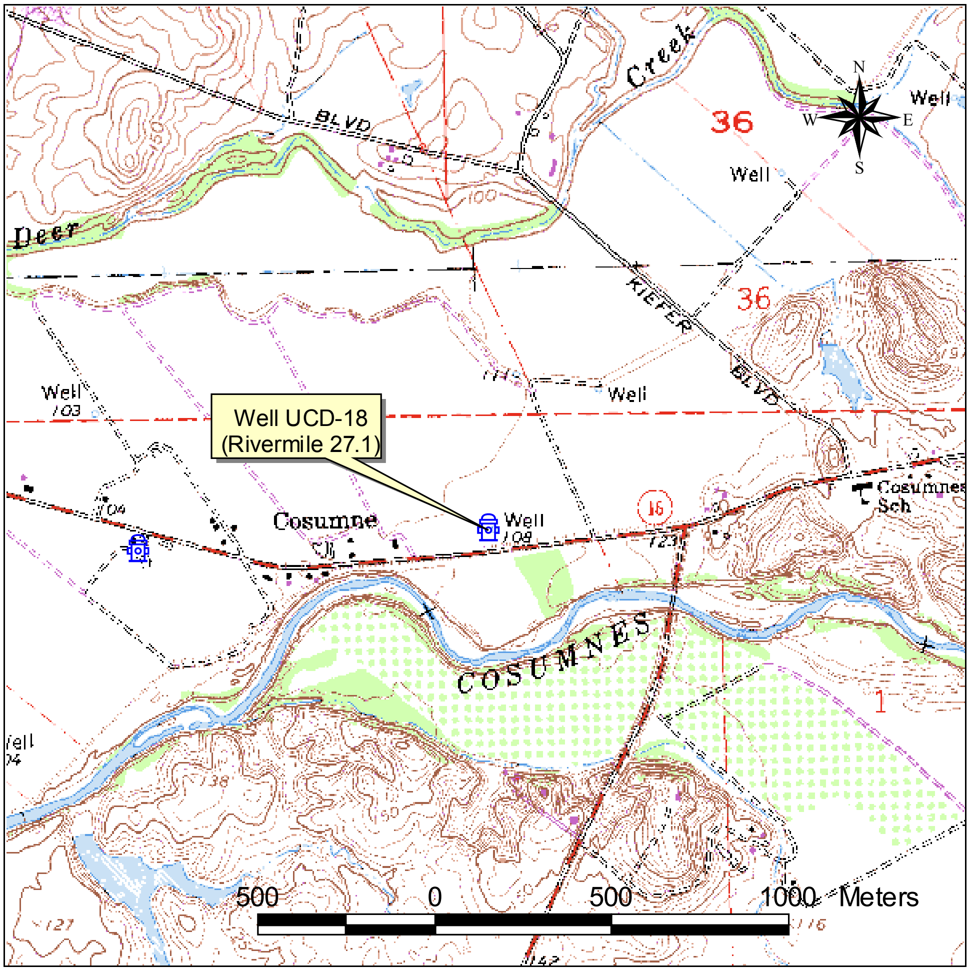
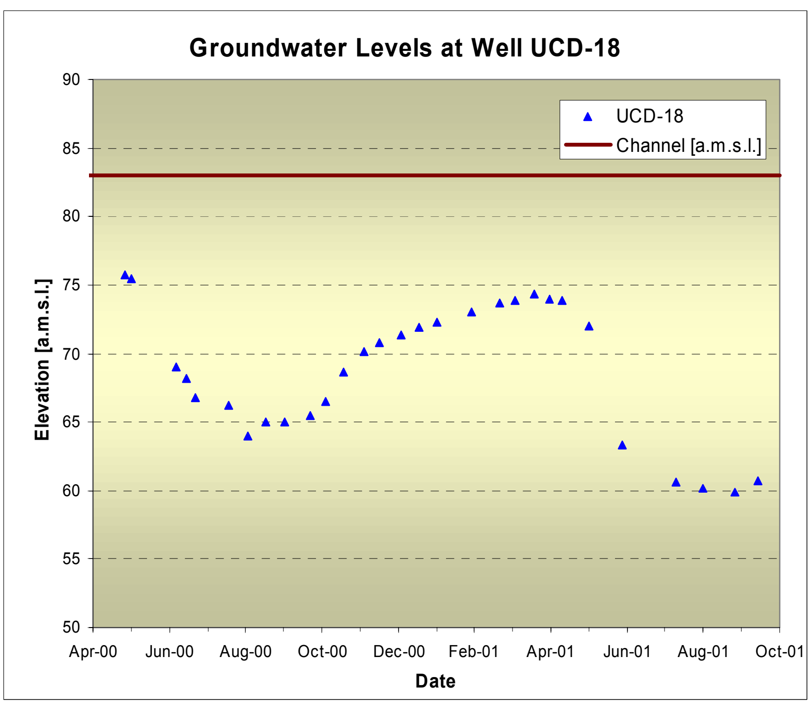


Figure 1 *Groundwater monitoring network run by UC-Davis*


Well UCD-18
(Rivermile 27.1)
Cosumne
COSUMNES
Deer
Creek
KIEFER BLVD
Well
36
N
S
E
W
500
0
500
1000
Meters


Groundwater Levels at Well UCD-18
UCD-18
Channel [a.m.s.l.]
Elevation [a.m.s.l.]
Date
90
85
80
75
70
65
60
55
50
Apr-00
Jun-00
Aug-00
Oct-00
Dec-00
Feb-01
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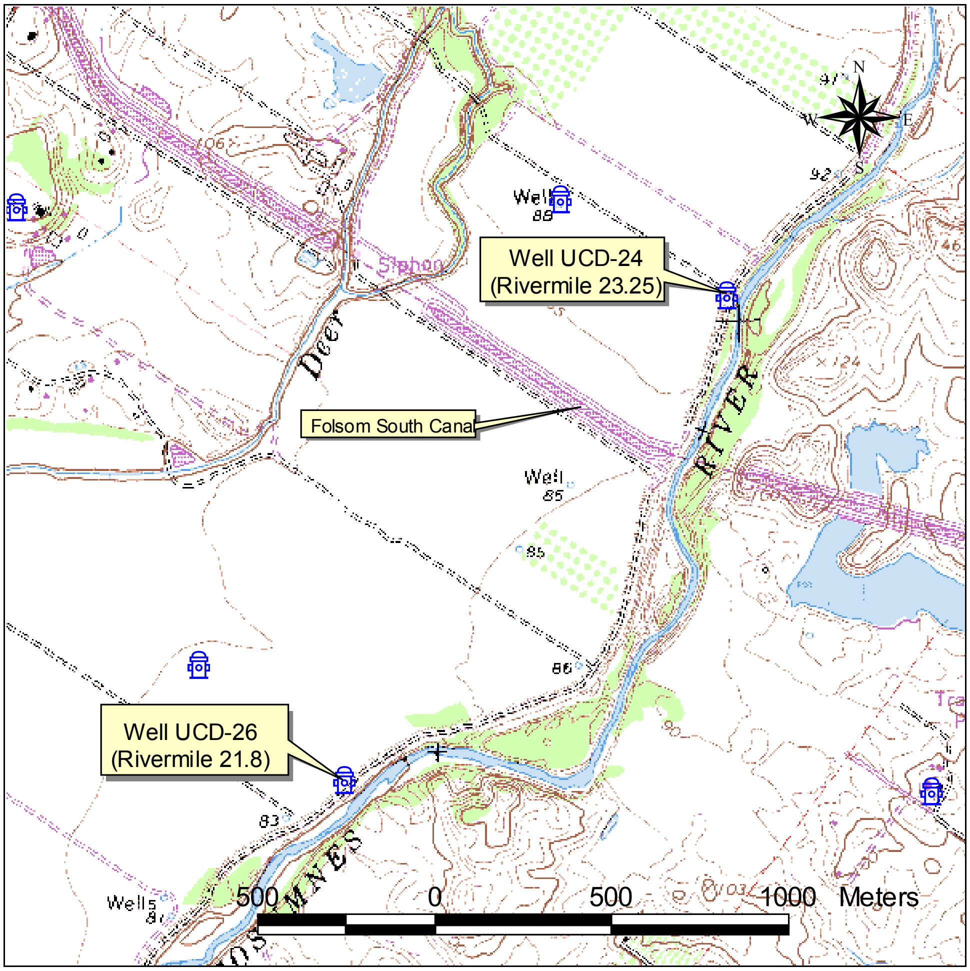
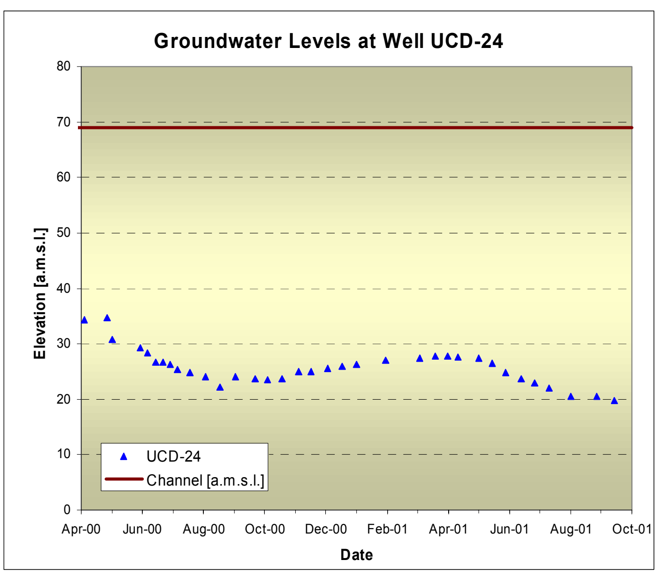
Jun-01
Aug-01
Oct-01


Well UCD-24
(Rivermile 23.25)
Folsom South Canal
Well UCD-26
(Rivermile 21.8)
Deer
RIVER
Siphon
500 0 500 1000 Meters
N
S
E
W


Groundwater Levels at Well UCD-24
Elevation [a.m.s.l.]
Date
UCD-24
Channel [a.m.s.l.]
0
10
20
30
40
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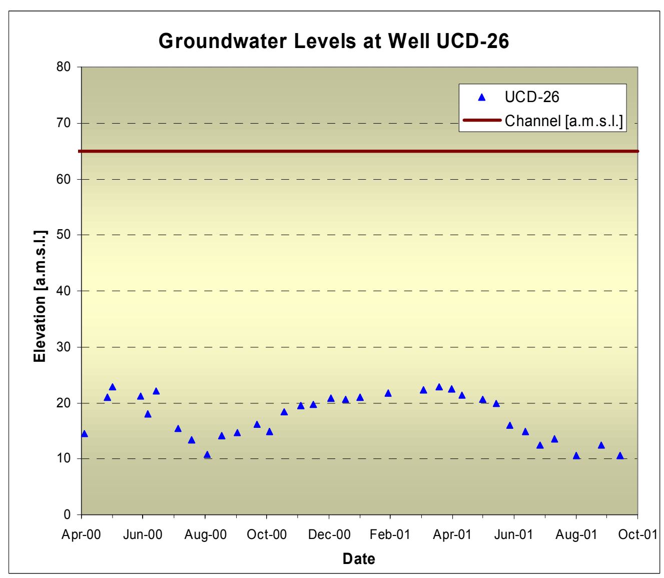
Jun-01
Aug-01
Oct-01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Date
UCD-26
Channel [a.m.s.l.]
0
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30
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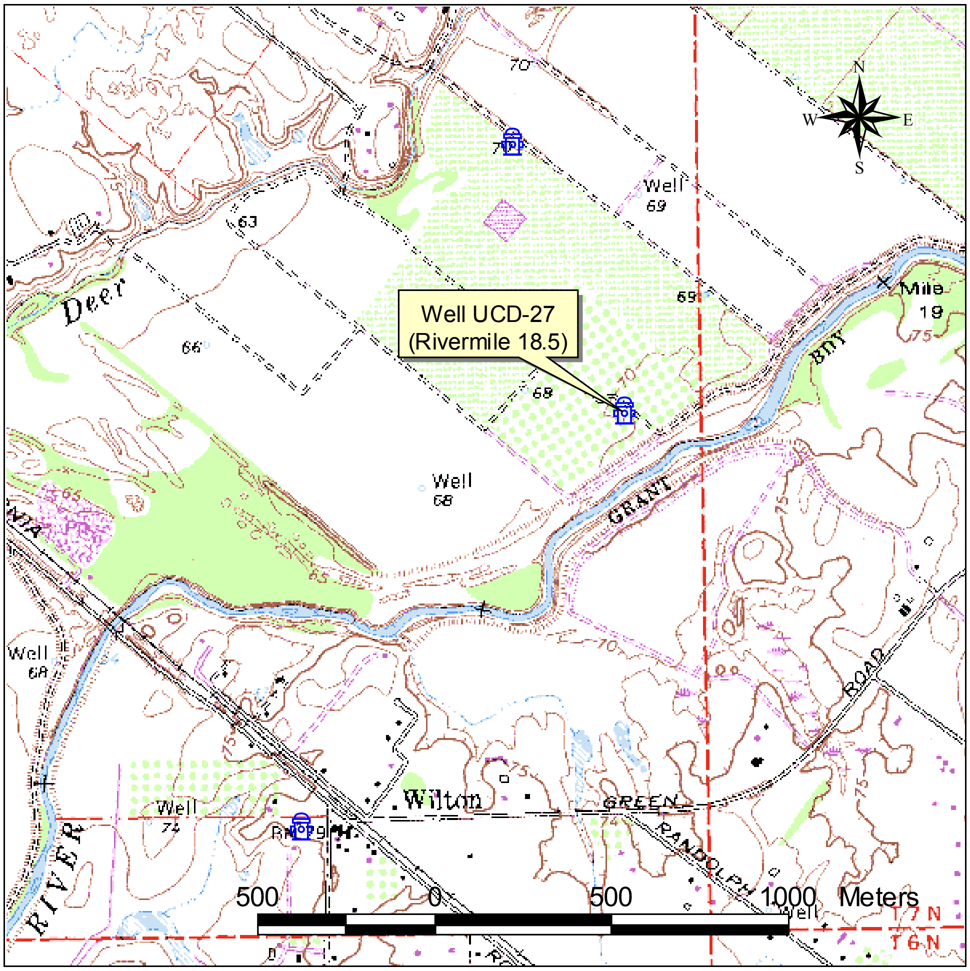
Jun-01
Aug-01
Oct-01


Well UCD-27
(Rivermile 18.5)
Deer
RIVER
GRANT
BAY
Mile
19
Well
69
Well
68
Well
74
Wilton
GREEN
RANDOLPH
ROAD
500
0
500
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Meters
T 7 N
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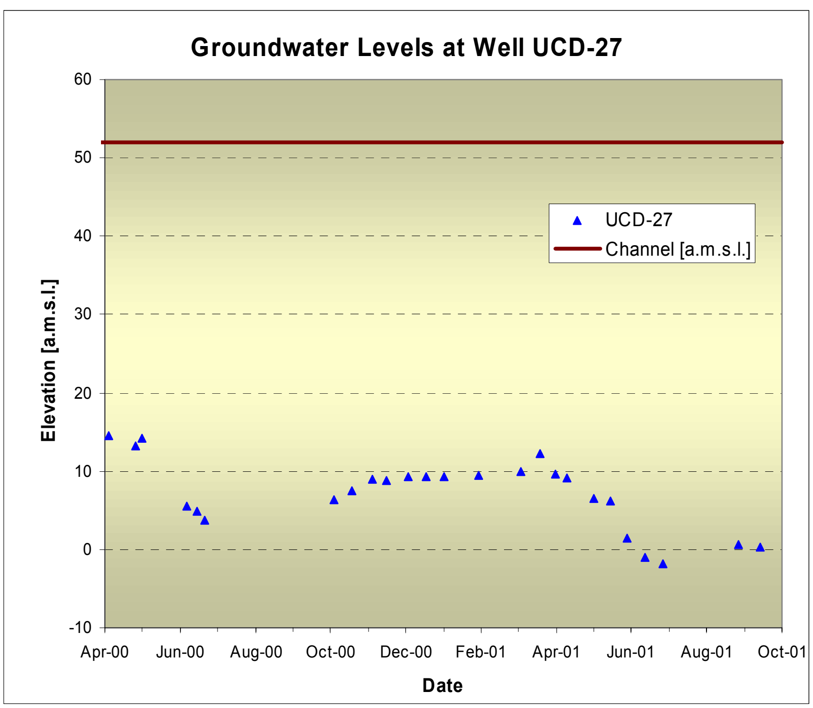
W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Elevation [a.m.s.l.]
Date
UCD-27
Channel [a.m.s.l.]
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40
30
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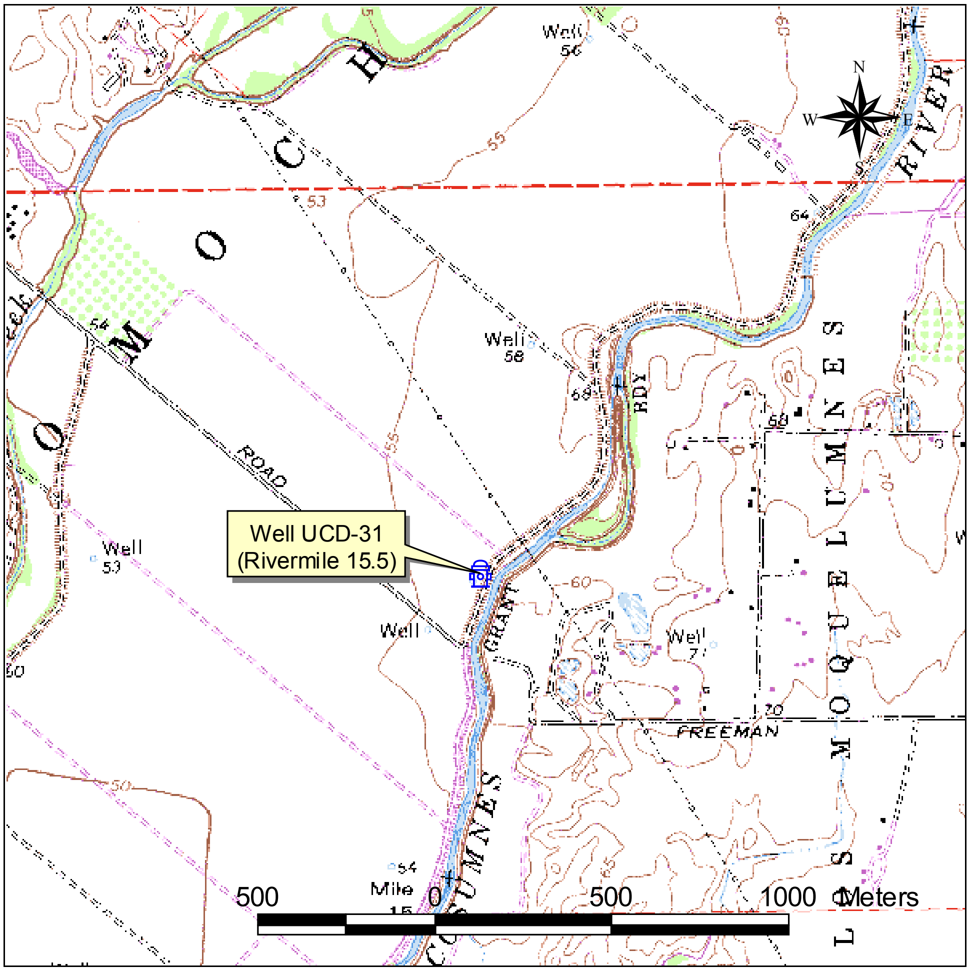
Jun-01
Aug-01
Oct-01


Well UCD-31
(Rivermile 15.5)
500
0
500
1000
Meters
N
S
E
W
ROAD
GRANT
FREEMAN
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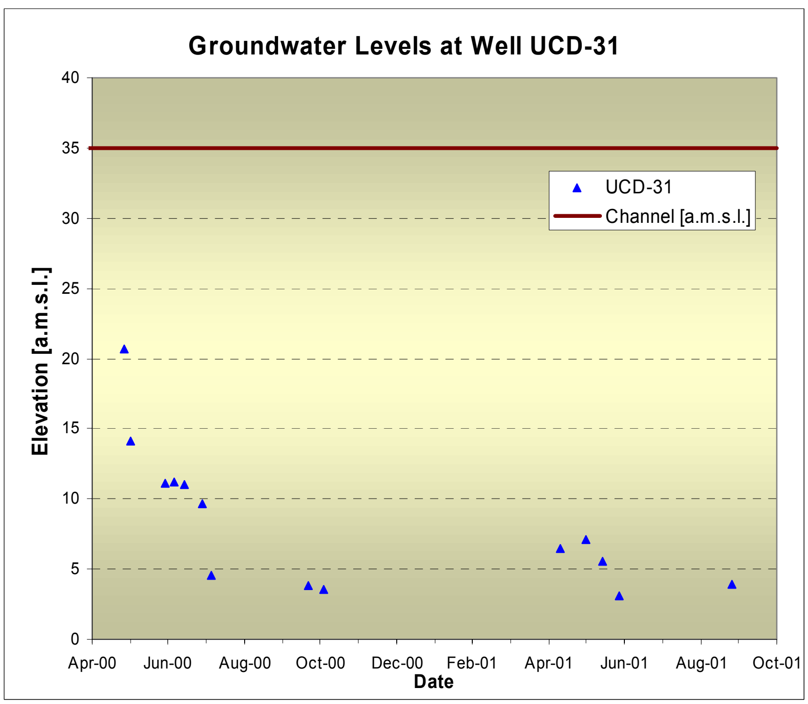
MOKELUMNE
RIVER
Well
Mile


Groundwater Levels at Well UCD-31
Elevation [a.m.s.l.]
Date
UCD-31
Channel [a.m.s.l.]
0
5
10
15
20
25
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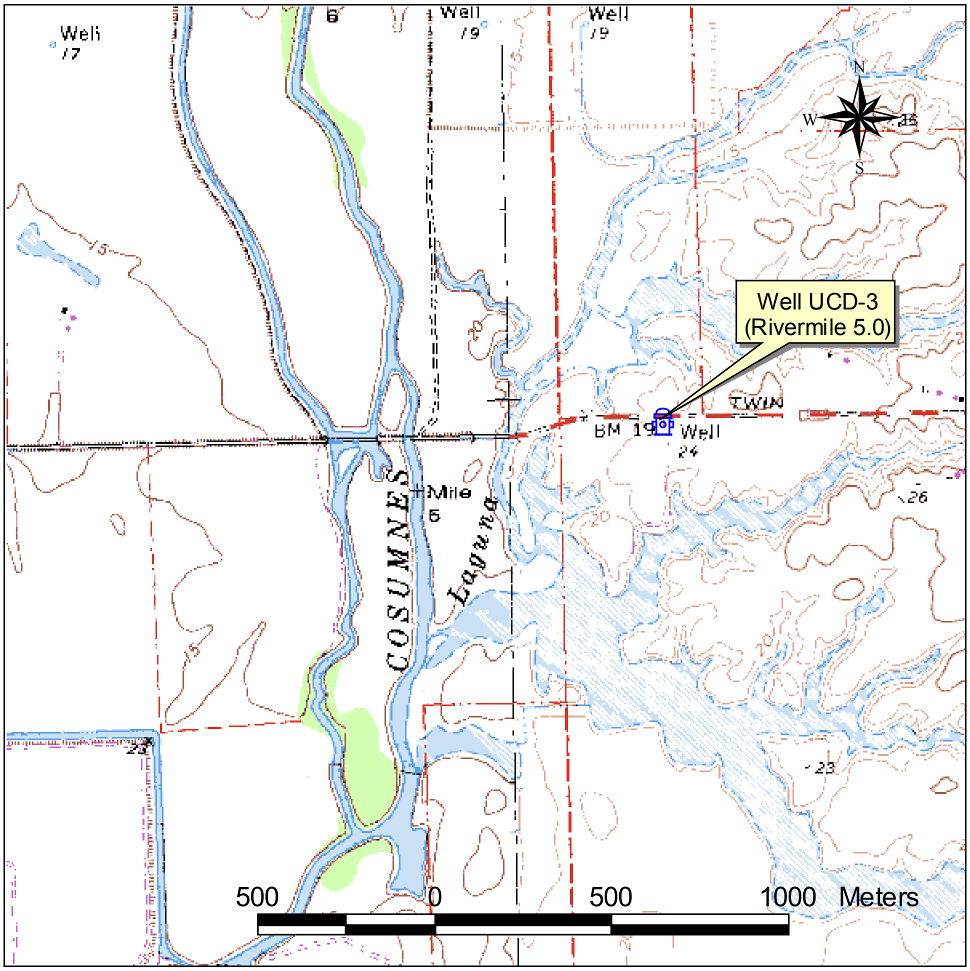
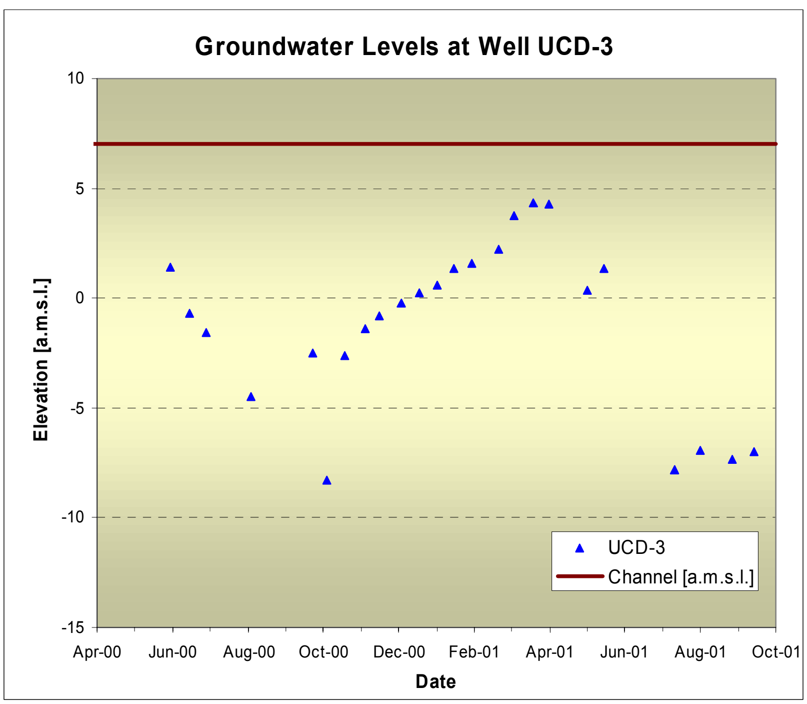
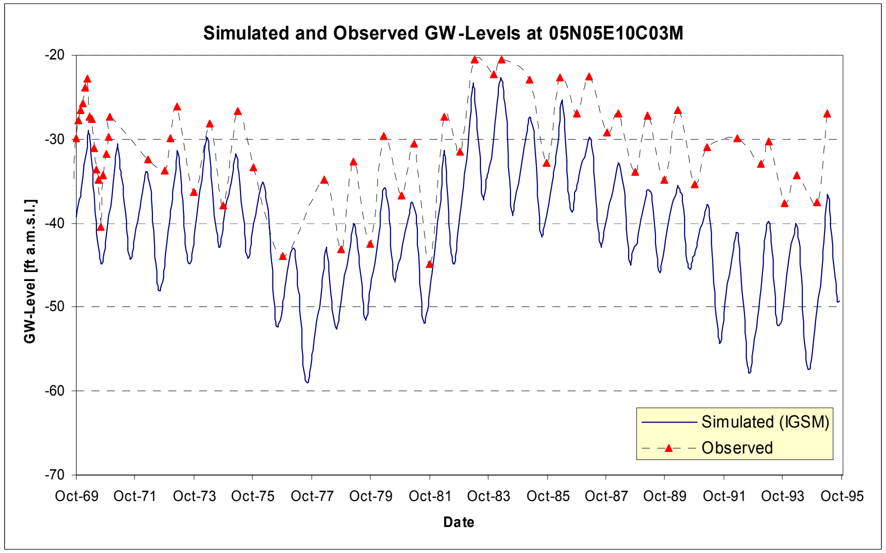
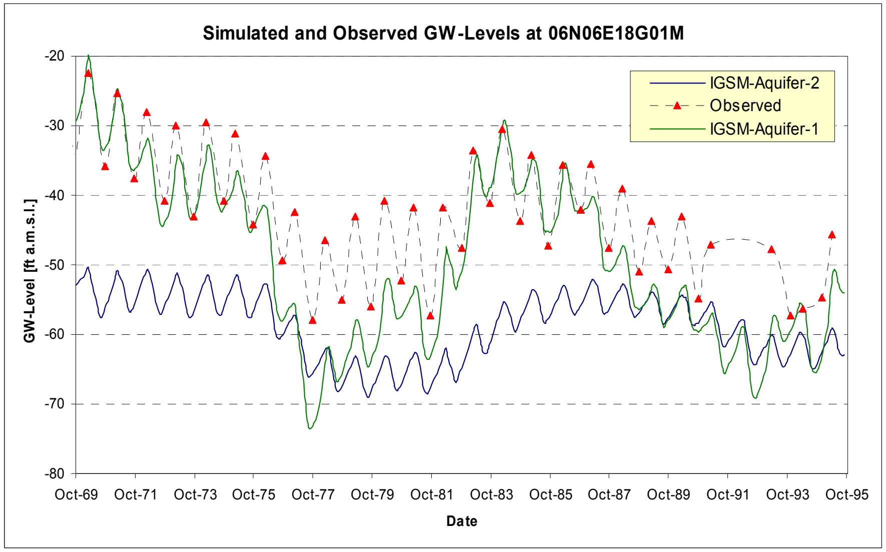
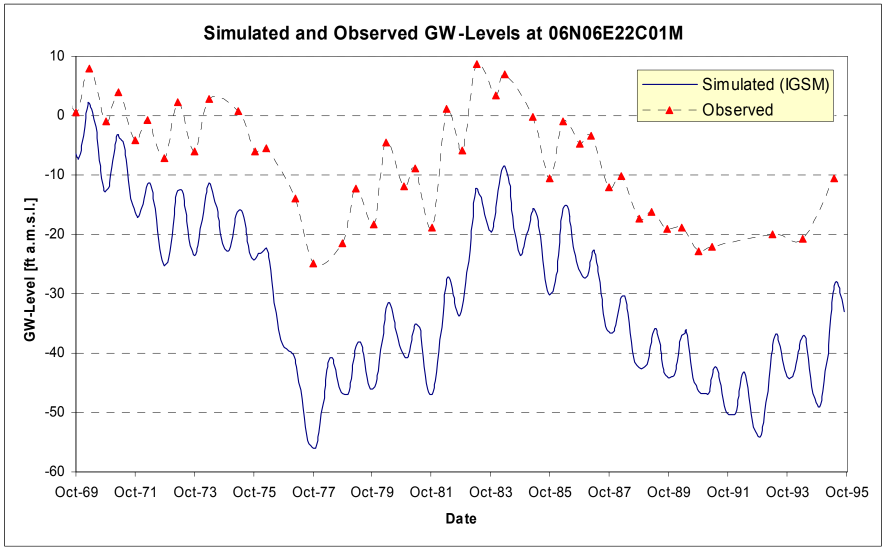
Jun-01
Aug-01
Oct-01

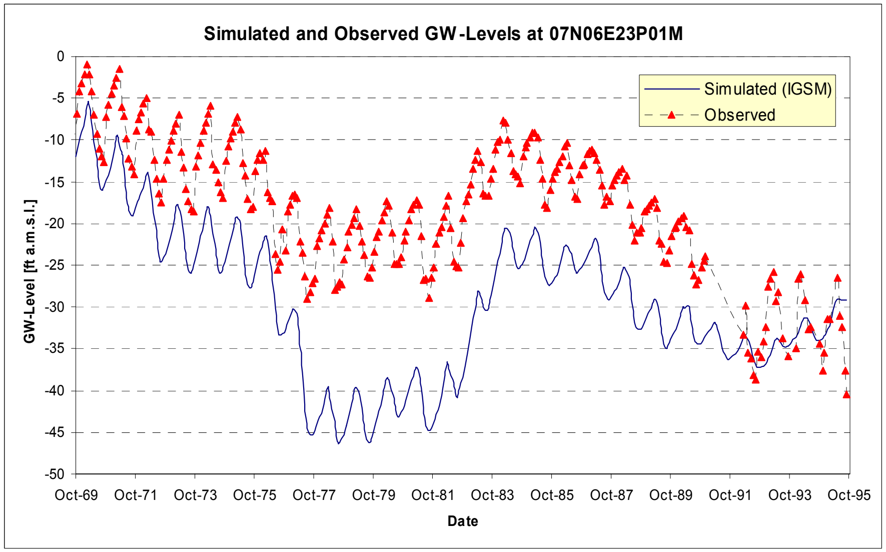

Well UCD-3
(Rivermile 5.0)
COSUMNES
Laguna
Mile
6
TWIN
BM 19
Well
24
N
S
W
E
500
0
500
1000 Meters

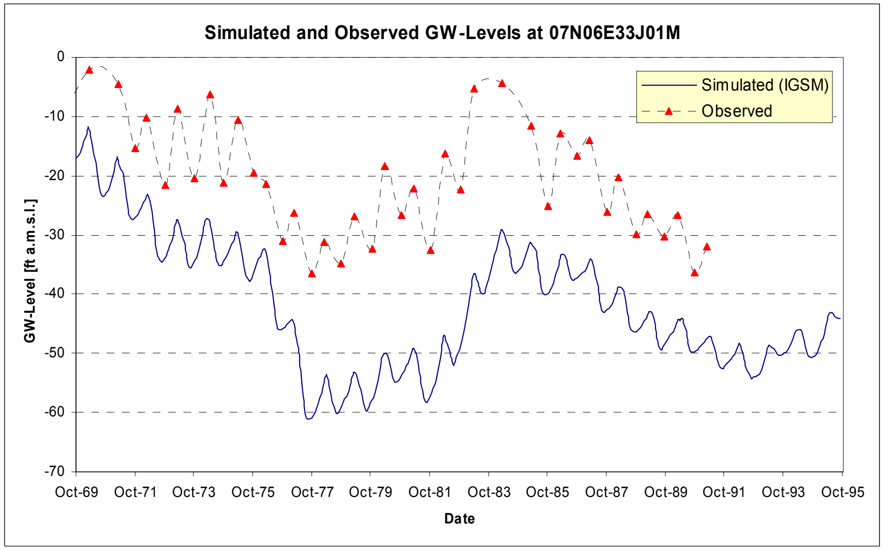

Groundwater Levels at Well UCD-3
Elevation [a.m.s.l.]
10
5
0
-5
-10
-15
Apr-00
Jun-00
Aug-00
Oct-00
Dec-00
Feb-01
Apr-01
Jun-01
Aug-01
Oct-01
Date
UCD-3
Channel [a.m.s.l.]

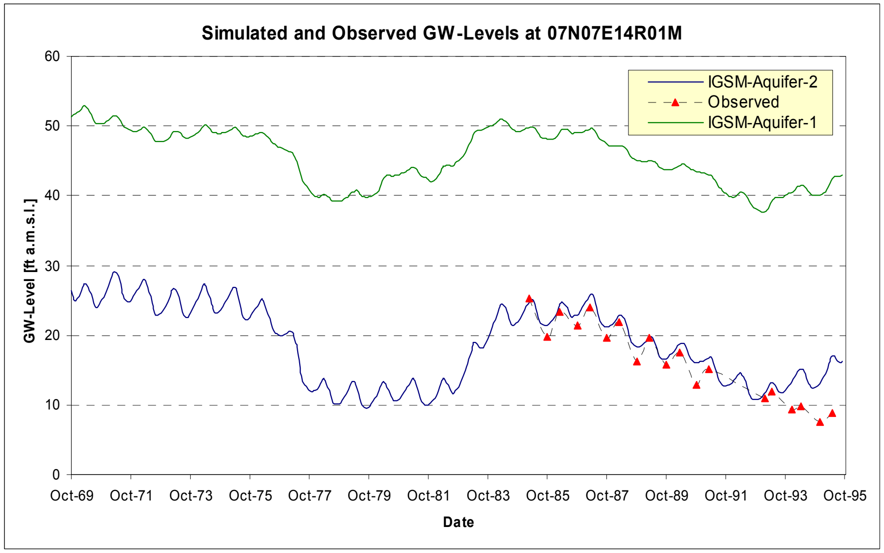

Simulated and Observed GW-Levels at 05N05E10C03M
GW-Level [ft a.m.s.l.]
-20
-30
-40
-50
-60
-70
Oct-69
Oct-71
Oct-73
Oct-75
Oct-77
Oct-79
Oct-81
Oct-83
Oct-85
Oct-87
Oct-89
Oct-91
Oct-93
Oct-95
Date
Simulated (IGSM)
Observed

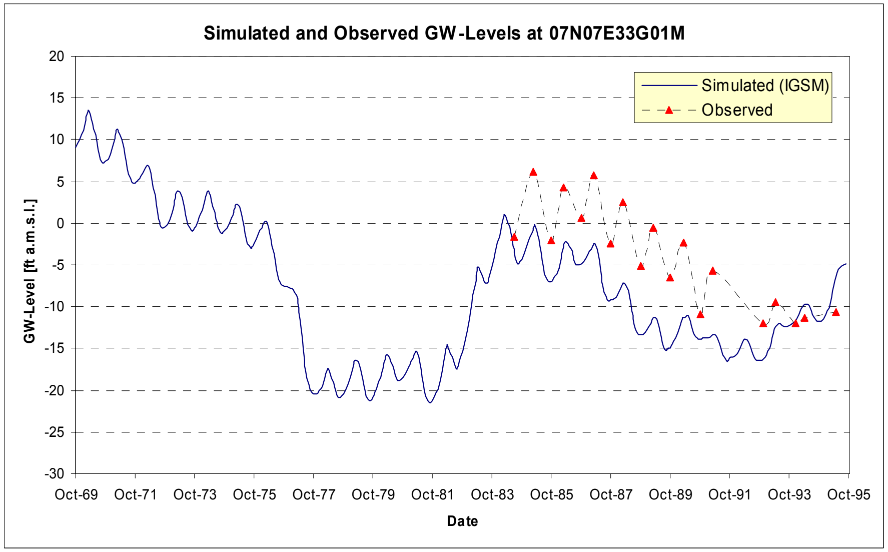

Simulated and Observed GW-Levels at 06N06E18G01M
GW-Level [ft a.m.s.l.]
-20
-30
-40
-50
-60
-70
-80
Oct-69
Oct-71
Oct-73
Oct-75
Oct-77
Oct-79
Oct-81
Oct-83
Oct-85
Oct-87
Oct-89
Oct-91
Oct-93
Oct-95
Date
IGSM-Aquifer-2
Observed
IGSM-Aquifer-1

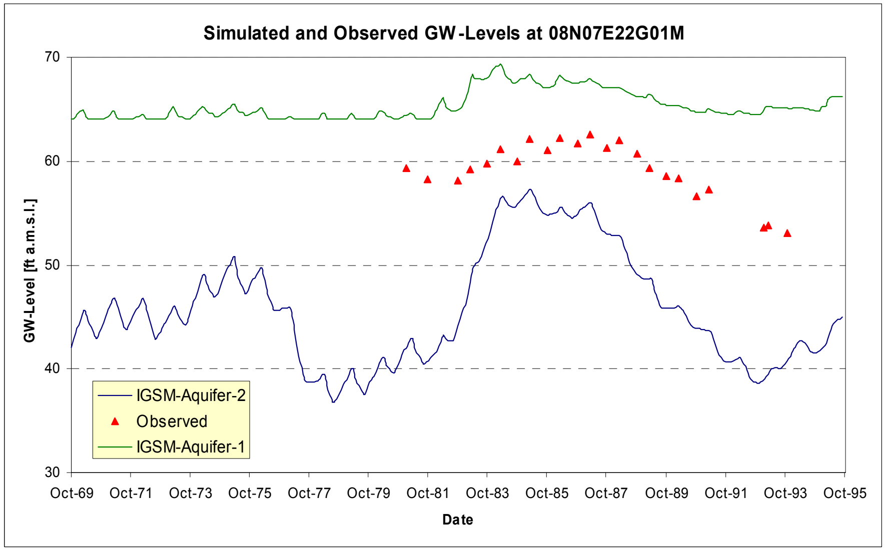

Simulated and Observed GW-Levels at 06N06E22C01M
GW-Level [ft a.m.s.l.]
10
0
-10
-20
-30
-40
-50
-60
Oct-69
Oct-71
Oct-73
Oct-75
Oct-77
Oct-79
Oct-81
Oct-83
Oct-85
Oct-87
Oct-89
Oct-91
Oct-93
Oct-95
Date
Simulated (IGSM)
Observed

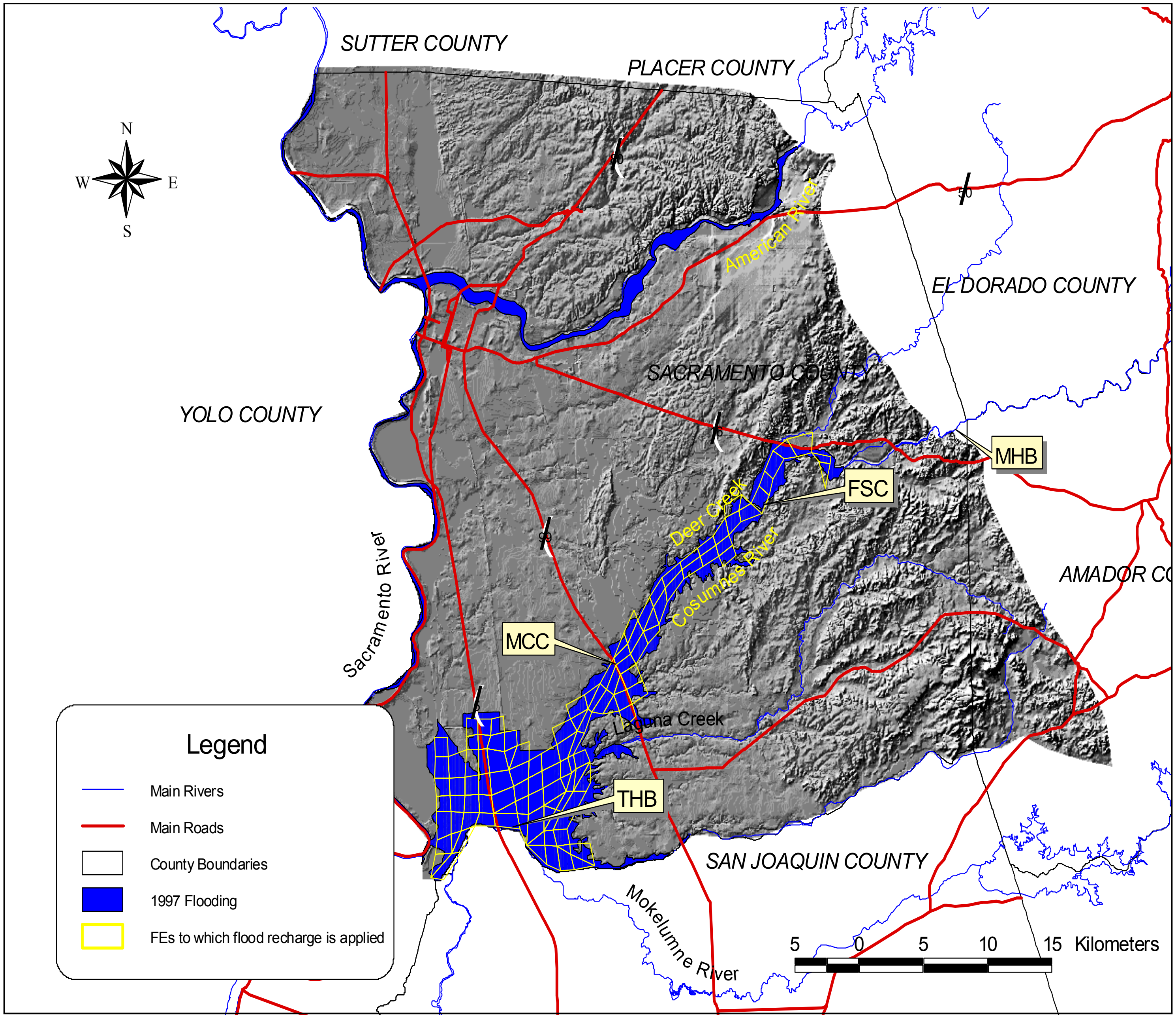

Simulated and Observed GW-Levels at 07N06E23P01M
GW-Level [ft a.m.s.l.]
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
-50
Oct-69
Oct-71
Oct-73
Oct-75
Oct-77
Oct-79
Oct-81
Oct-83
Oct-85
Oct-87
Oct-89
Oct-91
Oct-93
Oct-95
Date
Simulated (IGSM)
Observed


Simulated and Observed GW-Levels at 07N06E33J01M
Simulated (IGSM)
Observed
GW-Level [ft a.m.s.l.]
Date
0
-10
-20
-30
-40
-50
-60
-70
Oct-69
Oct-71
Oct-73
Oct-75
Oct-77
Oct-79
Oct-81
Oct-83
Oct-85
Oct-87
Oct-89
Oct-91
Oct-93
Oct-95


Simulated and Observed GW-Levels at 07N07E14R01M
IGSM-Aquifer-2
Observed
IGSM-Aquifer-1
GW-Level [ft a.m.s.l.]
Date
60
50
40
30
20
10
0
Oct-69
Oct-71
Oct-73
Oct-75
Oct-77
Oct-79
Oct-81
Oct-83
Oct-85
Oct-87
Oct-89
Oct-91
Oct-93
Oct-95


Simulated and Observed GW-Levels at 07N07E33G01M
Simulated (IGSM)
Observed
GW-Level [ft a.m.s.l.]
Date
20
15
10
5
0
-5
-10
-15
-20
-25
-30
Oct-69
Oct-71
Oct-73
Oct-75
Oct-77
Oct-79
Oct-81
Oct-83
Oct-85
Oct-87
Oct-89
Oct-91
Oct-93
Oct-95


Simulated and Observed GW-Levels at 08N07E22G01M
IGSM-Aquifer-2
Observed
IGSM-Aquifer-1
GW-Level [ft a.m.s.l.]
Date
70
60
50
40
30
Oct-69
Oct-71
Oct-73
Oct-75
Oct-77
Oct-79
Oct-81
Oct-83
Oct-85
Oct-87
Oct-89
Oct-91
Oct-93
Oct-95


SUTTER COUNTY
PLACER COUNTY
EL DORADO COUNTY
SACRAMENTO COUNTY
YOLO COUNTY
AMADOR CO
SAN JOAQUIN COUNTY
American River
Deer Creek
Cosumnes River
Sacramento River
Laguna Creek
Mokelumne River
MHB
FSC
MCC
THB
N
S
E
W
50
99
5 0 5 10 15 Kilometers
Legend
Main Rivers
Main Roads
County Boundaries
1997 Flooding
FEs to which flood recharge is applied